Departement für Pferde
Klinik für Pferdechirurgie
der Vetsuisse-Fakultät Universität Zürich

Direktor Klinik für Pferdechirurgie: Prof. Dr. med. vet. Anton Fürst, Dipl. ECVS, FVH Pferd

Arbeit unter wissenschaftlicher Betreuung von

Dr. med. vet. Jan Kümmerle, PhD, Dipl. ECVS, FTA für Pferde

The problem of pin breakage in equine transfixation pin casting: a retrospective clinical study and biomechanical testing of four different transfixation pin designs

Inaugural-Dissertation

zur Erlangung der Doktorwürde der
Vetsuisse-Fakultät Universität Zürich

vorgelegt von

Sara Keller

Tierärztin
von Basel, BS

genehmigt auf Antrag von

Prof. Dr. med. vet. Anton Fürst, Referent
Prof. Dr. med. vet. Ann Martens, Korreferentin

2018

Table of Contents

1 Summary	**3**
1.1 Zusammenfassung	4
2 Introduction	**5**
2.1 Threaded versus nonthreaded pins	6
2.2 Self-tapping versus nonself-tapping pins	6
2.3 Divergent versus non-divergent pins	7
2.4 Pin placement in metaphysis versus diaphysis	7
2.5 Number and size of inserted pins	7
2.6 Sequential drilling versus step drilling	8
2.7 Coated versus uncoated pins	9
2.8 Method of pin attachment in TPC	9
2.9 Walking cast and external skeletal fixation	10
2.10 Tapered-sleeve pin system	11
2.11 Complications of TPC	12
2.12 Current focus on pin breakage in TPC constructs	13
2.13 Aim and hypothesis of the study	14
3 Material and Methods	**15**
3.1 Case study	15
3.1.1 Surgery	15
3.2 Biomechanical testing	16
3.2.1 Study design	16
3.2.2 Preparation of the bones and pin insertion	16
3.2.3 Pilot study for evaluation of the test setup	18
3.2.4 Test setup using the simplified test model	20
3.2.5 Biomechanical testing	22
3.2.6 Radiographic evaluation after biomechanical testing	23
4 Results	**24**
4.1 Case study	24
4.2 Biomechanical testing	27
4.2.1 Pin insertion and experimental set-up	27
4.2.2 Results of the pilot study	27
4.2.3 Biomechanical testing	29
4.2.4 Failure mode and results of post-testing assessment of the bone-pin constructs	33

5 Discussion **34**
5.1 Case study 34
5.2 Biomechanical testing 36
5.2.1 Simplified test model 36
5.2.2 Mode and clinical relevance of biomechanical testing 36
5.2.3 Influence of pin design on results of biomechanical testing 37
5.2.4 Influencing factors and variations of the test setup 39
5.2.5 Limitations of the biomechanical study 39
5.3 Conclusions 39

7 References **41**

6 Acknowledgment

7 Curriculum Vitae

8 Annex

1 Summary

The goal of this thesis was to evaluate transfixation pin casting (TPC) for equine fracture treatment.
A clinical case study included 4 adult Warmblood horses with comminuted phalangeal fractures treated with TPC using centrally threaded Securos positive profile pins (SPPP), Imex positive profile pins (IPPP) or Imex thread run-out pins (ITROP). They all showed 1-4 pin breakages 2-28 days postoperatively. 3 horses were euthanized due to complications with TPC and internal fixation.
In a biomechanical study, cadaveric equine third metacarpal bones with 1 transfixation pin placed horizontally in the distal metaphysis were tested. In 3 groups of 8 bone pairs, an ITROP was inserted into one bone. The other pin type [IPPP, SPPP or smooth Steinmann pin (SSP)] was inserted contralaterally. The pins were tested under cyclic loading. The first compressive load level of 2000 N was applied with 50 N/s. Every load level was maintained for 10000 cycles, followed by an increase of 500 N each, until pin failure.
The centrally threaded PPPs failed at a mean of 29276 (SPPP) and 41179 cycles (IPPP), respectively, at 2500-4500 N. The ITROP failed at a mean of 31061 cycles at 3000-4000 N. With a mean of 48685 cycles to failure, the SSP was significantly more resistant against cyclic failure than the ITROP. The SSP failed at 4000-5000 N.
Despite the superior performance of the SSP, the simplified test model does not allow a direct advice for clinical use. Clearly, further studies are necessary.

Keywords: equine fracture treatment, transfixation pin casting, pin breakage, biomechanical testing

1.1 Zusammenfassung

Ziel der Arbeit war es, Transfixationspincasts (TPC) zur Frakturbehandlung beim Pferd zu evaluieren.
In einer Fallstudie wurden 4 Warmblutpferde mit Trümmerfrakturen des Fessel- bzw. Kronbeins verglichen, die mit 2 Transfixationspins mit zentralem Gewinde [Securos Pins mit positivem Gewinde (SPPP), Imex Pins mit positivem Gewinde (IPPP), oder Imex Pins mit auslaufendem Gewinde (ITROP)] therapiert wurden. Alle Fälle zeigten 2-28 Tage postoperativ 1-4 Pin-Brüche. 3 Pferde wurden wegen Komplikationen mit dem TPC und der internen Fixation euthanasiert.
In der biomechanischen Studie wurden Kadaverknochenpaare mit 1 horizontal in die distale Röhrbeinmetaphyse eingesetzten Transfixationspin getestet. In 3 Gruppen zu je 8 Knochenpaaren wurde ein ITROP in einen Knochen und ein anderer Pin-Typ [IPPP, SPPP, glatter Steinmann Pin (SSP)] in den kontralateralen Knochen eingesetzt. Nach einer Vorlast von 100 N wurden die Pins unter zyklischer Druckbelastung getestet. Die erste Laststufe betrug 2000 N bei 50 N/s. Jede Laststufe dauerte 10000 Zyklen und wurde um 500 N pro Laststufe erhöht, bis zum Pin-Bruch.
Die Pins mit zentralem positivem Gewinde versagten nach 29276 (SPPP) und 41179 (IPPP) Zyklen bei 2500-4500 N. Der ITROP versagte bei 31061 Zyklen bei 3000-4000 N. Der SSP hatte eine signifikant höhere Bruchfestigkeit mit 48685 Zyklen und 4000-5000 N.
Trotz der Überlegenheit der SSP erlaubt das vereinfachte Testmodell keine direkte klinische Empfehlung. Dazu sind weitere Studien nötig.

Schlüsselwörter: Frakturbehandlung beim Pferd, Transfixationspincast, Pin-Bruch, biomechanische Studie

2 Introduction

The treatment of horses suffering from fractures of the proximal (P1) and middle (P2) phalanx can be very challenging. To prevent complications like laminitis in the contralateral limb, it is essential that the horse is able to bear weight on the operated limb immediately after surgery. Therefore, the fracture has to be stabilised very well (Joyce et al., 2006; Nemeth and Back, 1991). A particular challenge is the treatment of comminuted fractures. Comminuted fractures typically occur when a bone is loaded at a fast rate. The rate dependency of bone means that a bone loaded rapidly is stiffer and fails at a higher load. The greater area under the load-deformation curve means that more energy is released during breakage compared to fractures that occur at slow loading rates. This high level of energy release leads to comminution of the bone (Lopez and Markel, 2012). Moderately comminuted fractures are those that still have an intact strut of bone between the two articular surfaces of the affected bone and the majority of the fragments can be stabilised with internal fixation. Severely comminuted fractures have no intact strut of bone and stabilisation with internal fixation is not satisfactory (Auer, 2012; Kraus et al., 2004).

For this reason, the method of transfixation pin casting (TPC) has been developed for treatment of severely comminuted distal fractures. To create a TPC construct, transfixation pins are inserted horizontally into the distal part of the third metacarpal/metatarsal (MCIII /MTIII) bone and their ends are then incorporated into a fibreglass cast (Fig. 1). This system allows the transfer of the axial weight-bearing forces through the pins into the cast to avoid collapse of the fracture site (Auer, 2012; Joyce et al., 2006; Lescun et al., 2007; Rossignol et al., 2014).

It was shown that, compared to a traditional short or full-limb cast, the TPC significantly reduces the bone strain in P1 as well as the displacement on a 30° osteotomy site in MCIII (Hopper et al., 2000; Hopper et al., 1998a; McClure et al., 1994b; Schneider et al., 1998).

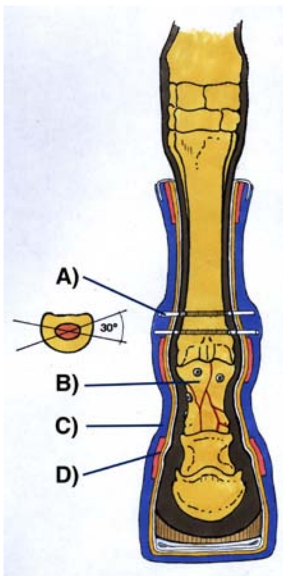

Fig. 1: Schematic illustration of a TPC. A) Two centrally threaded PPP inserted parallel (each 15° divergent from the dorsal plane, thus diverging by 30° from each other) into the distal metaphysis of MCIII.
B) Comminuted fracture of P1 reduced with cortex screws placed in lag fashion, C) fibreglass cast, D) additional padding. Illustration by Matthias Haab, University of Zurich.

2.1 Threaded versus nonthreaded pins

There are different pin designs available which influence the insertion technique as well as the holding power. The main types used are threaded and nonthreaded pins. It was shown that threaded pins have an increased holding power compared to smooth pins which tend to loosen faster under cyclic loading (Anderson et al., 1993; Aron et al., 1986; Clary and Roe, 1995; Egger et al., 1986; Morisset et al., 2000; Palmer et al., 1992). Although threaded pins have a higher pullout strength compared to smooth pins, they break at stress-concentrating points, i.e. the junction of the threaded to the nonthreaded part, especially if the threaded part has a reduced core diameter. Therefore, the concept of centrally threaded positive profile pins (PPP) was developed. PPP have the advantage of a consistent inner diameter and thus reduce the risk of pin breaking, but still have the advantage of increased holding power (Clary and Roe, 1995; Martens et al., unpublished data; Morisset et al., 2000; Palmer et al., 1992). It was shown that a TPC construct with two 6.35 mm centrally threaded PPP and a TPC with four 4.8 mm smooth Steinmann pins lead to a similar reduction of strain on the dorsal aspect of P1 under axial compression (Williams et al., 2014).
In clinical studies, no significant difference was found in short-term survival of horses treated with smooth Steinman pins compared to threaded pins (Joyce et al., 2006; Lescun et al., 2007). Nevertheless, it was shown that threaded pins stayed stable 33% longer than smooth pins (Lescun et al., 2007). Furthermore, threaded pins have a lower incidence of osteolysis and pin-tract infection than smooth pins (Aron et al., 1986; McClure et al., 2000).

2.2 Self-tapping versus nonself-tapping pins

The design and insertion technique of centrally threaded PPP also vary and influence bone-temperature during insertion and the development of microfractures. There are two types of centrally threaded PPP: self-drilling, self-tapping pins (SDST, large animal transfixation/casting pin with central thread, Imex, Longview, Texas, USA) and nonself-drilling, nonself-tapping pins (NDNT, Pearson positive pin, Jorgenson Laboratories Inc, Loveland, Colorado, USA). For the NDNT transfixation pins, the pinholes have to be predrilled and -tapped, whereas the SDST transfixation pins are inserted in one step without any predrilling of the pinhole. SDST pin insertion increases the temperature in the surrounding bone significantly and causes more macroscopic and microscopic damage to the bone compared to NDNT pins. Also, NDNT pins have a higher pull-out strength compared to SDST pins. This shows that NDNT pins have a better initial pin stability which leads to reduced short-term pin loosening (Morisset et al., 2000).
Another research group compared self-tapping positive profile transfixation pins (STTP, thread with asymmetric buttress profile, equine transfixation pin, Securos Inc, Fiskdale, Massachusetts, USA) to nontapping positive profile transfixation pins (NTTP, symmetric V threads, large animal transfixation pin, Imex, Longview, Texas, USA) (Bubeck et al., 2010). For both pin types, the pilot hole was predrilled with sequential drilling. For the STTP, the pins were inserted after creation of the pilot hole, whereas for the NTTP, the holes had to be pretapped before pin insertion. They also found that STTP caused a significant increase in bone temperature compared to the NTTP. But contrary to the first study, no significant difference between the pull-out strengths were found and the STTP caused less microdamage (Bubeck et al., 2010).

In summary, STTP have the same initial stability in the bone as NTTP, but STTP are more likely to induce thermal bone necrosis during insertion, which could lead to pin loosening (Bubeck et al., 2010; Morisset et al., 2000).

2.3 Divergent versus non-divergent pins

The transfixation pins may be inserted either parallel to each other or with a divergency from each other in one plane. Note that in most publications, the divergence of the pins is defined as “30° divergent in the frontal plane”. In our opinion, this description applies the anatomical nomenclature not correctly. For this reason, we describe this position of the pins as “each pin is inserted diverging 10-15° from the dorsal plane so that, finally, the pins diverge by 30° from each other” in our study. *In vitro* studies of McClure et al. (1994a) showed that MCIII bones with two divergent pins placed in the distal diaphysis and metaphysis are significantly stronger compared to MCIII bones with parallel pins when tested under torsion. Concerning the prevention of displacement of an osteotomy site, no difference was found between pins placed parallel or divergent. However, the authors still recommend the use of divergent pins (McClure et al., 1994b).

2.4 Pin placement in metaphysis versus diaphysis

Another variability in TPC-application is the location of pin insertion in the MCIII bone. They may be placed either in the metaphysis or the distal diaphysis. In an evaluation of the holding power of centrally threaded PPP placed in the metaphysis compared to pins placed in the diaphysis, the diaphysis provided greater resistance to axial extraction (McClure et al., 2000). However, further case studies showed that all secondary fractures through a pinhole occurred when pins were placed in the diaphysis and that pin loosening occurs faster when pins were placed at a diaphyseal site (Joyce et al., 2006; Lescun et al., 2007). Therefore, it is recommended to place the pins in the metaphysis (Auer, 2012). At this location, there is a large amount of cancellous bone which is less brittle than cortical bone, has a higher toughness and fails at a higher strain (Rossignol et al., 2014). This is further supported by clinical observations that pins inserted in the diaphysis are associated with more complications such as ring sequestrum formation and secondary fractures (Auer, 2012).

2.5 Number and size of inserted pins

As the pins have to resist great forces in TPC, the strongest implants available are being used. The pin strength increases substantially with the increase of the core diameter as the stiffness is directly related to the fourth power of the pin radius (r) (Palmer et al., 1992). This is because the bending stiffness of an object is described by the product E (modulus of elasticity) x I (area moment of inertia). The area moment of inertia of cylindrical objects such as pins is calculated as $I = \pi r^4/4$ (Muir et al., 1995).
However, larger pin diameters also result in bigger holes and, therefore, larger cortical defects (Seltzer et al., 1996). A number of studies investigated the effect of pinhole size or cortical defect size on the torsional strength of different bones of different species. Seltzer et al. (1996)

performed biomechanical tests with equine MCIII with either 7.94 mm (5/16 inch) or 9.53 mm (3/8 inch) bicortical holes. This was equivalent to a bicortical defect of 22% to 33% of the bone diameter, respectively. Both defect sizes resulted in reduced torsional structural properties of the bones with an approximately 20% reduction in failure torque in each group. However, bones with the smaller holes, i.e. 7.94 mm, still had some postyield plastic deformation capability whereas bones with the larger holes immediately progressed to failure after the yield point. The authors of this study hypothesize that this difference might be important clinically because the partially retained postyield deformation potential would allow an animal to respond to the pain associated with reaching the yield point by protecting the limb and prevent catastrophic failure (Seltzer et al., 1996). Another study that investigated the effect of differently sized circular defects on the torsional strength of sheep femora found that defects of 10% of the bone diameter caused no significant reduction of the torsional strength. Defects over 10% acted as stress concentrators and defects of 20% of the bone diameter reduced the torsional strength by 34%. Defects of 20% to 60% of the bone diameter reduced the torsional strength in a linear manner (Edgerton et al., 1990).
Hopper et al. (1998b) investigated the effect of pinhole size and number on *in vitro* bone strength of equine radii. On one side of the bone pair, they drilled a 6.35 mm hole, which was equivalent to 14 to 20% (mean 17%) of the dorsopalmar bone diameter and on the contralateral side, they drilled a 9.5 mm hole, which was equivalent to 23 to 30% (mean 26%) of the dorsopalmar diameter. The study showed that cortical defects of 14% to 20% of the dorsopalmar bone diameter lead to no significant reduction of the torsional strength, whereas cortical defects of 23% to 30% of the dorsopalmar bone diameter significantly decreased the torsional strength of the radii by 13.2%. Concerning pin number, they found out that there was no significant difference in mean torsional strength of the radii in the control group without any pins and the radii with one, three or six transcortical pins. But there was a trend of the radii in the control group to be stronger than those in the 3- and 6-hole groups (reduction of 17.2% of the bone strength for the 6-hole group) (Hopper et al., 1998b).
In summary, it is recommended that the pin diameter should not exceed 20% of the dorsopalmar bone diameter to avoid significant reduction of torsional strength (Edgerton et al., 1990; Hopper et al., 1998b; McClure et al., 2000). Radiographic geometric evaluations of equine long bones showed that the diameter of the 6.35 mm large-animal pins represents less than 20% of the total dorsopalmar width of the metaphysis of the MCIII in adult horses of 410 kg to 550 kg (Hanson and Markel, 1994; McClure et al., 2000).
Regarding the optimal number of pins inserted into the bone, there were no significant results in the study mentioned above. However, since bone strength was decreased by 17.2% in the 6-hole group, it is recommended and generally accepted to use 2 or 3 transcortical pins (Auer, 2012; Hopper et al., 1998b; Joyce et al., 2006; McClure et al., 2000; Rossignol et al., 2014).

2.6 Sequential drilling versus step drilling

To create drill holes, two different methods are available, i.e. sequential drilling and step drilling. In sequential drilling, the hole is increased with three differently sized drill bits to the required dimension (4.5 mm, 5.5 mm and 6.2 mm for a 6.35 mm PPP). The step drill bit consists of three different diameters in a single drill bit (increasing from 4.5 mm to 5.5 mm and 6.2 mm) and each step has a length of 2 cm. With this step drill, the hole can be created without changing the drill bit. In an *in vitro* study, there was no significant temperature difference found between sequential drilling and step drilling at 60 N and 120 N drilling force, respectively. At 80 N drilling force there was a significant increase in temperature by 2.13° C when using the step drill bit as compared to sequential drilling. The authors still regard step drilling as a good alternative to sequential drilling because the time to finish the drill hole when using the step drill bit only took one-quarter of the time and step drilling did not cause excessive heat generation (Bubeck et al., 2009). The step drill bit is available for centrally threaded PPP. Of the implants that are currently relevant, the Securos® pin represents a centrally threaded PPP that comes with a step drill bit. Additionally, these Securos® pins are self-tapping in contrast to the Imex® pins, which are nonself-tapping.

2.7 Coated versus uncoated pins

Another variation in pin design is coated vs. uncoated. It is possible to coat the PPP with hydroxyapatite (HA), which is the main inorganic crystalline component of the bone matrix and builds the rigid bone structure. In human medicine, HA-coating is used to prevent pin loosening as it promotes the bone ingrowth into the HA surface of the pin (Zacharias et al., 2007). A recent equine study showed that HA coated pins required lower insertion torque than uncoated pins. The extraction torque after 8 weeks was not significantly different between HA coated versus uncoated pins but torque reduction was lower in HA-coated pins. Also 5 out of 15 HA coated pins upheld or increased their stability over the course of an 8-week-*in vivo* study whereas all uncoated pins loosened. However, pin hole radiolucency and clinical variables were not different between HA-coated and uncoated pins (Lescun et al., 2012). Zacharias et al. (2007) additionally investigated if there is a difference between plasma-sprayed hydroxyapatite (PSHA), biomimetic hydroxyapatite (BMHA) and uncoated PPP concerning heat generation and required torque during insertion into equine MCIII bones. They found similar insertion characteristics in BMHA and uncoated pins. PSHA required higher insertional torque and generated higher temperatures, which were above the critical temperature to cause thermal damage to the osteocytes. They found that PSHA is not practicable for clinical use as 4 out of 18 PSHA pins were unmovable after insertion and one PSHA pin insertion led to a fracture of the bone. The BMHA pins performed similar to the uncoated PPP and further *in vivo* studies to determine osteointegration will be needed.

2.8 Method of pin attachment in TPC

There are different ways of attaching the transfixation pins into a cast. McClure et al. (1996) studied four attachment methods. They compared normal incorporation of the pin into the cast with other methods that contained different systems with washers and nuts as well as steel halos. They could not show any significant difference between these methods under axial compression and assumed that incorporating the pins into the cast was satisfactory. Rossignol et al. (2014) investigated in an *in vivo* study if a new hybrid cast consisting of plaster of Paris and fibreglass layers, both applied in a figure-of-eight tour around the pins with two additionally integrated fibreglass splints, provides more stability. Two 6.3 mm centrally threaded PPP were placed in the epiphysis and distal metaphysis in a coplanar position that were maintained for 6-8 weeks (except in one case where the pins were left in place for three months). None of the pins were loose at the time of pin removal after 6-8 weeks, and 9 out of

11 horses survived (82%). This method seems to be a good alternative to reduce the risk of pin loosening. Alternatively, other factors such as the very distal placement of the pins and, consequently, the high ratio of cancellous to cortical bone could be responsible for the favourable results and there was no control group.

2.9 Walking cast and external skeletal fixation

The walking cast as used by Nemeth and Back (1991) incorporates Steinmann pins and a U-shaped steel frame into a plaster of Paris cast (Nemeth and Back, 1991). Studies that compared traditional TPC with U-shaped steel frame incorporated into a fibreglass cast showed that there is no significant difference with or without a walking bar (McClure et al., 1994b).

An alternative to the traditional TPC is the external skeletal fixator (ESF) where the transfixation pins are attached to a sidebar. The comparison of the stabilization of a radial osteotomy using two novel ESF and a traditional full-limb TPC, showed that a solid ESF was stiffer and stronger than TPC or modular ESF and failed at a higher number of cycles compared to TPC (Nutt et al., 2010). The modular ESF consists of two modular sidebars that allow to adjust the pin placement individually, whereas the solid ESF has one solid and one modular sidebar. One advantage of the ESF is the possibility of wound treatment in open fractures eliminating the need for repeated cast changes (Nutt et al., 2010). The original external skeletal fixation device ESFD, developed by Nunamaker et al. (1986), consisted of three unprotected negative profile transfixation pins with a diameter of 9.6 mm on the threaded side and a core diameter of 8.6 mm in the nonthreaded side. For the *in vitro* studies, the pins were placed in the MCIII bone and then attached to a U-shaped sidebar that incorporates a foot plate and the shoe (Nunamaker et al., 1986). This system allowed immediate full-weight bearing after surgery, but 22% of the cases fractured through a pinhole in the MCIII bone (Kraus et al., 2004; Nunamaker and Nash, 2008; Nunamaker and Richardson, 1992; Nunamaker et al., 1986).

In 2001, a new ESFD with tapered-sleeve transcortical pin (TSP) system was developed (Fig. 2) (Nash et al., 2001).

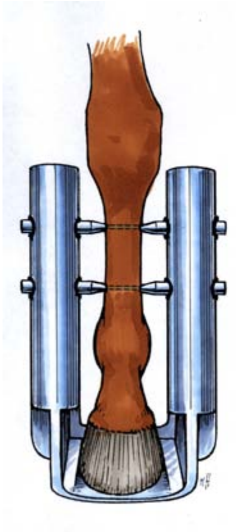

Fig. 2: Schematic illustration of an external skeletal fixation device. Two tapered sleeves were slipped over the transcortical pins and tightened to the U-shaped external fixator. Illustration by Matthias Haab, University of Zurich.

2.10 Tapered-sleeve pin system

The tapered sleeves extend from the metal frame to the bone surface and the sleeves are slipped over both sides of the smooth transcortical pin. The pins have threaded ends so that the tapered sleeves may be fastened and compressed against the bone. The TSP-ESFD has been developed for decreasing the stress at the bone-pin interface (BPI). Bending forces make up 90% of the total stress at the BPI with conventional pins, leading to peak stresses at the outer cortex (Auer, 2012; Huiskes et al., 1985; Nash et al., 2001; Nunamaker and Nash, 2008). With the tapered sleeves, the supporting diameter outside the bone is increased, so that the pin is under shear loading and not bending forces anymore (Nash et al., 2001). Nash et al. (2001) showed in single cycle to failure and cyclic fatigue tests that the TSP-ESFD is significantly stiffer than the conventional pins and that the stress at the BPI is distributed more evenly.
Elce et al. (2006) included the TSPs into a full-limb fibreglass cast (TSP-TPC) and compared it to a conventional full-limb TPC. Single cycle to failure tests of cadaveric limbs with a distal radial osteotomy showed that the TSP-TPC had a significantly higher mean load to failure than the conventional full-limb TPC (Elce et al., 2006).
Another newly developed system is the pin-sleeve cast (PSC), where a sleeve (hollow cylinder) is inserted into the bone and a smooth pin is slipped inside the sleeve and is tightened to a ring fixator (Fig. 3). The pin is only contacting the sleeve at two circular supports, allowing the pin to bend slightly during weight bearing. This leads to minimized strains at the bone-sleeve interface. The displacement at a standard load stays comparable to an identical segment stabilized with a conventional TPC (Auer, 2012; Brianza et al., 2010).

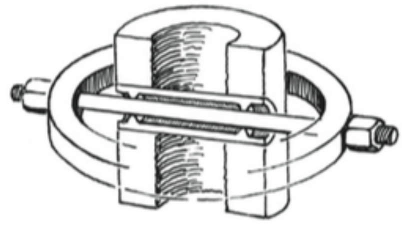

Fig. 3: Schematic illustration of a novel pin-sleeve cast (PSC). The pin is slipped into the sleeve and tightened to the ring fixator. From Auer, J.A. 2012. Principles of Fracture Treatment, In: Auer, J.A., Stick, J.A. (Eds.) Equine Surgery (Fourth Edition). Elsevier Saunders, St. Louis, 1’047-1’081.

2.11 Complications of TPC

Benefits of TPC are the preservation of blood supply at the fracture site, avoidance of surgical trauma to the surrounding soft tissues and load removal from the fracture site. But besides the known disadvantages of external coaptation such as osteoporosis, pressure sores, contralateral laminitis, contracted feet and tendon laxity, there are some additional complications associated with TPC (Auer, 2012). Since the pin is in contact with the environment, pin tract infection is a quite common complication. Pin loosening, induced by cyclic loading, is suspected to promote the establishment of infections (Aron and Toombs, 1984; Aron et al., 1986; Clary and Roe, 1995; Green, 1981; Nunamaker and Nash, 2008; Palmer et al., 1992). The other way around, pin tract infection definitely accelerates pin loosening (Palmer et al., 1992). A pin tract infection can lead to ring sequestrum formation with an acute onset of lameness (Auer, 2012). Other complications are secondary fractures through a pinhole and implant failure (Auer, 2012; Bubeck et al., 2010; Joyce et al., 2006; Lescun et al., 2007; Martens et al., unpublished data; McClure et al., 1995; Nemeth and Back, 1991). Pin loosening is the result of complex processes and is the most common complication associated with ESF (Aron and Toombs, 1984; Aron et al., 1986; Clary and Roe, 1995; Morisset et al., 2000; Palmer et al., 1992). Factors related to pin loosening include implant design and material used, pin insertion location and technique, type of the external fixator, applied loads and number of cycles. Also bone quality and quantity as well as the osseous response to pin insertion and loading is contributing to the development of pin loosening (Clary and Roe, 1995; Morisset et al., 2000; Palmer et al., 1992). Premature pin loosening is associated with reduction of stability at the fracture site and even lameness (Auer, 2012; Clary and Roe, 1995; Joyce et al., 2006; Morisset et al., 2000; Palmer et al., 1992). Pin loosening predisposes for pin tract infections and secondary fractures through the pinhole (Aron and Toombs, 1984; Egger et al., 1986; Green, 1981; Morisset et al., 2000).
Pin insertion technique has a high impact on the development of pin loosening since the insertion temperature determines bone resorption and ultimately long-term stability of the pin. At temperatures of 47°C, delayed death of osteocytes may occur but is not seen before three weeks after insertion. Bone resorption is caused by exposure to temperatures of 47°C for 1 min (Bubeck et al., 2009; Eriksson and Albrektsson, 1983; Morisset et al., 2000). Heat generation increases when bone debris accumulates at the cutting edge of the drill bit because it enhances friction (Bubeck et al., 2009). Microfractures may be the result of pin insertion

and also contribute to the development of premature pin loosening (Egger et al., 1986; Morisset et al., 2000).
Important factors contributing to pin hole fractures are the application of excessively large pins in relation to the bone diameter and placing the pin too far proximal (Joyce et al., 2006; Lescun et al., 2007; Rossignol et al., 2014). The risk of a catastrophic fracture through the pin hole also increases by osteoporosis, ring sequestrum formation around the pin and pin hole osteolysis, because the pin hole is enlarged (Auer, 2012; Lescun et al., 2012).

2.12 Current focus on pin breakage in TPC constructs

Currently, the most frequently used method to treat comminuted P1 and P2 fractures in equine patients is to place two centrally threaded PPP with a 6.3 mm core diameter in the metaphysis or distal diaphysis of MCIII /MTIII and each 15° divergent from the dorsal plane (Auer, 2012; Joyce et al., 2006; McClure et al., 2000; McClure et al., 1994a; Rossignol et al., 2014). However, there are reports that these centrally threaded PPP tend to break under weight bearing even though they have ideal mechanical properties (small grain size associated with high strength, hardness and toughness) (Martens et al., unpublished data). It was shown that this might be associated with the surface quality of these pins (Martens et al., unpublished data). Deep scratches in the pin surface that occurred during machining steps, as well as grinding marks and fabrication imperfections function as stress concentrators. Another factor in stress concentrating is the general design of the positive-profile transfixation pins. Changes in the thread and core shaft diameter of the pins and the angulations of the threads as well as the depth of the threads are factors that contribute to fatigue failure of the implant during cyclic stress loading (Martens et al., unpublished data).
Griffin et al. (2011) published a new pin design with a negative thread design called a tapered thread run-out (TRO) half-pin for use in small animal surgery. These TRO pins have an increased shaft diameter and the TRO design reduces the acute junction of the threaded to the non-threaded part of the pin (Fig. 4) (Griffin et al., 2011). They compared these TRO half-pins with positive-profile threaded half-pins, showing an increased stiffness of the new TRO system and increased resistance to cyclic fatigue (Griffin et al., 2011). For horses, the Imex 6.3/8.0 mm Duraface® pins with thread run-out design (ITROP) became available recently. However, we are not aware of any studies evaluating the biomechanical properties of these pins.

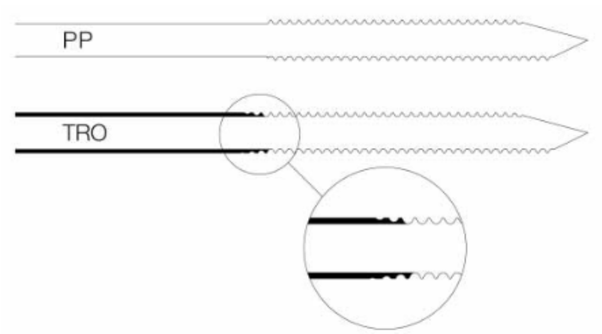

Fig. 4: Graphic illustration of a PPP and a TRO pin. From Griffin, H., Toombs, J.P., Bronson, D.G., Ross, J.D., Browne, R.H., 2011. Mechanical evaluation of a tapered thread-run-out half-pin designed for external skeletal fixation in small animals. Veterinary and Comparative Orthopaedics and Traumatology 24, 257-261.

Clinical observations indicate that there could be a difference between the centrally threaded PPP of the two companies, Imex and Securos, that supply the pins commonly used for TPC in horses. Some clinicians have the impression that Securos PPP might have a lower tendency to break compared to the traditional Imex PPP (Martens, Tessier, Fürst – personal communication 2015). An explanation for this impression could be that the comparison of optical and scanning electron microscope images of Imex and Securos centrally threaded PPP showed that Imex centrally threaded PPP have fabrication imperfections in two planes (transversal and longitudinal groves), whereas these imperfections are only present in the longitudinal plane in Securos centrally threaded PPP (Martens et al., unpublished data).

2.13 Aim and hypothesis of the study

Serious complications such as pin loosening or pin breaking are associated with the current method of transfixation casting. New implants such as the ITROP or the Securos 6.2 mm centrally threaded positive profile pins (SPPP) with a newly designed step drill bit have the potential to reduce these complications.
The aim of this thesis is to contribute to the knowledge and prevention of pin breakage in horses treated with TPC by

I) Describing clinical cases of pin breakage retrospectively
II) Comparing the biomechanical properties of the new ITROP, the Imex 6.3 mm centrally threaded positive profile pins (IPPP), the SPPP and a 6.1 mm smooth Steinmann pins (SSP) (Synthes, West Chester, Pennsylvania, USA) under cyclic loading.

Our first hypothesis is that pin breakage can occur with all the tested pin types under clinically relevant loading conditions.
Our second hypothesis is that the new ITROP is biomechanically superior to the SPPP, the IPPP and the traditional SSP under cyclic loading conditions relevant in equine TPC patients.

3 Material and Methods

3.1 Case study

All horses that were treated with TPC in the Equine Hospital of the University of Zurich between 2014 and 2015 were included in the case study and evaluated retrospectively based on the medical records. Information retrieved included breed, sex, age and weight of the horses, type and location of the fractures, type of internal fixations as well as number, type, localisation and divergence of the inserted pins. Further, the number, type, location and time to pin-related problems and the number and details of the re-surgeries were evaluated. The outcome was documented with the time until final pin removal and discharge from the hospital, complications not related to the TPC and the survival rate.

3.1.1 Surgery

Surgery was performed under general anaesthesia with the horses placed in lateral recumbency with the fractured limb uppermost. Internal fixation was performed first. Then, two transfixation pins were inserted. The distal pin was placed in the metaphysis, 4 to 5 cm proximal to the distal articular surface of MCIII/MTIII, and the proximal pin was placed in the distal diaphysis, 2 to 3 cm proximal to the distal pin. Each pin was inserted parallel to the articular surface of MCIII/MTIII but with a 15° divergence from the dorsal plane so that, finally, the pins were diverging 30° from each other.
Before drilling, an aiming device was placed on the bone via two stab incisions created with a No. 10 scalpel blade. Then, a 3.2 mm drill bit was introduced through the device. Drilling was always performed under irrigation with a sterile saline solution. A 3.2 mm pilot hole was then drilled in all patients. The further drilling procedure depended on the type of the pin inserted. For the IPPP and ITROP, sequential drilling was used to enlarge the drill hole, starting with a 4.5 mm drill bit, followed by a 5.5 mm and a 6.2 mm drill bit. Tapping was then performed using the designated Imex tap for the IPPP and ITROP.
For the SPPP, the Securos® equine sequential drill bit was used with a diameter that increases after every 20 mm of length of the drill bit, starting with 4.5 mm at its tip, followed by a diameter of 5.5 mm and 6.2 mm to enlarge the drill hole. Then, the self-tapping pin was inserted.
Before the application of the casting material, the legs were first padded with a double layer of stockinet. Then, the proximal end of the cast, the proximal sesamoid bones and the coronet were padded with extra layers of synthetic cotton padding. Additionally, the parts in between were padded with one layer of synthetic cotton padding. Altogether, the padding layers had a thickness of 1.5 – 2 cm. Then, 7-8 rolls of a fibreglass/polyurethan resin cast material (Nemoa Cast, Orthocare, QLD, Australia) with a width of 10-12.5cm were used to incorporate the pins into a half-limb cast. For this purpose, the cast was either placed in a figure-of-eight pattern around the pin ends or small slits were created in the cast material during application at the site of the pins. Recovery from general anesthesia was performed with the assistance of head and tail ropes.

3.2 Biomechanical testing

3.2.1 Study design

Biomechanical testing of four different transfixation pins was performed on 24 pairs of equine cadaver MCIII with a single pin inserted in each bone (Fig. 5). The type of this pin determined allocation of each bone to group ITROP, IPPP, SPPP or SPP.
Testing was performed using pairs of limbs in a comparative fashion with the ITROP pin used as the reference.
Specifically, three comparative tests on 8 pairs of cadaver MCIII for each test were performed with

- Group 1: **ITROP** vs. **SSP**
- Group 2: **ITROP** vs. **SPPP**
- Group 3: **ITROP** vs. **IPPP**

Within each test, an ITROP pin was inserted in 4 randomly selected left and 4 right MCIII and the other pin in the corresponding contralateral bone of each pair of limbs.

Fig. 5: The four different pin designs used in this study. A) Imex 6.3 mm centrally threaded positive profile pin (IPPP). B) Imex 6.3/8.0 mm Duraface® pin with thread run-out design (ITROP). C) Securos 6.2 mm centrally threaded positive profile pin (SPPP). D) 6.1 mm smooth Steinmann pin (SSP).

3.2.2 Preparation of the bones and pin insertion

The 24 pairs of cadaver front limbs were harvested from horses euthanized or slaughtered for reasons unrelated to this study and with no history of orthopaedic disease. Limbs were kept at -20°C after harvesting until needed. The limbs were then wrapped in moist towels and thawed at room temperature for 14 to 18 h. The metacarpus of each limb was isolated and dissected free from all soft tissues. Each bone was marked with a number on a label that was attached around the lateral splint bone. To determine the exact site of pin location and to rule out any disorder of the bones, a dorsopalmar radiograph was taken of each bone using a direct radiography system (Fujifilm, Gierth HF400, high frequency diagnostic x-ray unit, Riesa, Germany) set at 80 kV and 10 mAs. A 20 gauge hypodermic needle was placed as a radiographic marker to determine the intended site of pin insertion in the distal metaphysis of MCIII, approximately 1 cm proximal to the physeal scar. Depending on the size of the bone, this corresponded to a distance of 35 to 41 mm proximal to the most distal aspect of the MCIII condyle. The intended medial entry and lateral exit points of the pin at MCIII were marked with a pen.

One pin was then implanted in the distal metaphysis of each MCIII in a medial to lateral direction according to the manufacturers' instructions.

To create the first drill hole, an aiming device was placed on the marked entry and exit points on the bone and a 3.2 mm drill bit was introduced through the device. A 3.2 mm pilot hole was then drilled in all specimens. The following drilling sequence depended on the type of pin inserted. During all drilling procedures, water irrigation of the drill bit was performed using tap water at room temperature applied manually with a syringe. Tapping was performed if required for the insertion of a specific pin based on manufacturer's instructions.

For the IPPP and ITROP, the 3.2 mm drill hole was enlarged sequentially by using a 4.5 mm drill bit, followed by a 5.5 mm and 6.2 mm drill bit. Tapping was then performed using the Imex tap for 6.3 mm/8.0 mm Duraface® full-pin for large animals before the pin was inserted.

For the SPPP the designated Securos® equine sequential drill bit was used after creation of the initial 3.2 mm hole. This sequential drill bit has a diameter of 4.5 mm at its tip that increases stepwise to 5.5 mm and 6.2 mm after every 20 mm length of the drill bit. Then, the self-tapping pin was inserted.

For the SSP, the 3.2 mm hole was first enlarged with a 4.5 mm drill bit, followed by a 5.5 mm and finally a 6.0 mm drill bit prior to pin insertion.

All pins were inserted from medially to laterally, so that the ends of the pins protruding from the medial and lateral cortex, respectively, were of equal length (Fig. 6).
After pin-insertion, the bones were wrapped in moist cloths and frozen (-20° C) until biomechanical testing was performed. This biomechanical testing was performed directly on these bone-pin constructs without application of casting material.

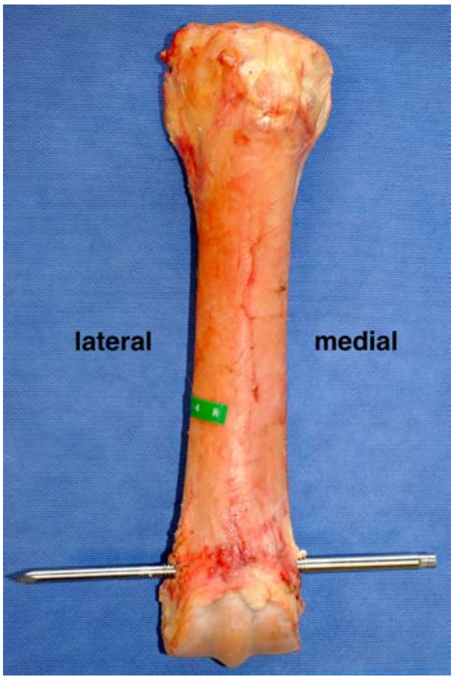

Fig. 6: MCIII bone with ITROP inserted in the distal metaphysis.

3.2.3 Pilot study for evaluation of the test setup

To evaluate the accuracy of the simplified test model without casting material (Fig. 7a), it was compared to a model with fibreglass cast (Fig. 7b) in a biomechanical pilot study before performing the biomechanical tests on the 24 pairs of MCIII.
For this pilot study, an SSP was inserted into the distal metaphysis of each MCIII of a pair of cadaver bones and one leg was equipped with fibreglass cast and the other leg was mounted to the simplified test model. For the cast model, the bone with the inserted pin was wrapped with two layers of padding material and an elastic bandage (Elastomull), resulting in a padding layer with a thickness of approximately 2 cm. On the distal end of the bone, a round foam with a thickness of 4 cm and with a diameter similar to the bone diameter was attached to the bone with an elastic bandage (Elastomull). Then, four bandages of cast material (4 cm width, 3M Scotchcast, Maplewood, Minnesota, USA) were applied. The proximal 4 cm of the bone were not included in the cast to allow fixation of the bone into the testing apparatus. Then, the distal part of the bone with the TPC was moulded with methacrylate into an aluminium ring (diameter = 12 cm). Then the TPC-construct was mounted to the testing apparatus (Fig. 7b).

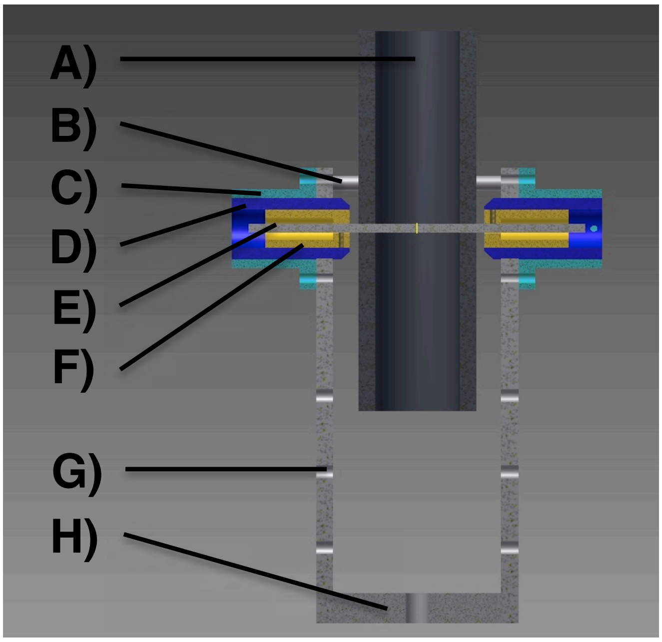

Fig. 7a: Transverse section of the setup for the simplified test model: A) Bone, B) stainless steel rod, C) outer stainless steel sleeve, D) inner stainless steel sleeve, E) pin, F) POM-C sleeve, G) side walls, H) ground plate.

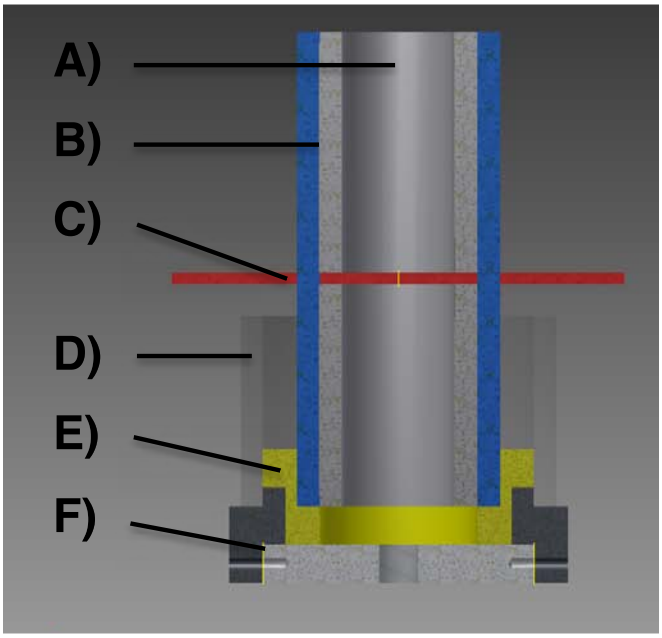

Fig. 7b: Transverse section of the setup for the cast model. A) Bone, B) cast- and padding-material, C) pin, D) aluminium cylinder, E) bone cement, F) ground plate.

For the evaluation of the simplified test model compared to the cast model, two runs of cyclic loading were performed on the same bone pair (one bone with the TPC model, one bone with the simplified test model). For run 1 (r1), the bones were loaded five times from Fo = 100 N to F2 = 1’000 N with axial compression resulting in 4-point bending of the pin. Then, the load F2 was increased by 500 N for each load level, each load level was maintained for 50 cycles and the specimens were loaded with a frequency of 1 Hz. The simplified test model was run for 250 cycles at a maximum load of F2 = 3’000 N, but the cast model was stopped early at

200 cycles and a maximum load of F2 = 2’500 N. For run 2 (r2), the bones were previously loaded with the same increasing loads as in r1 (start at F2 = 1’000 N, load increased by 500 N every 50 cycles and loaded with a frequency of 1 Hz). Then, the bones were loaded at the same load level Fu = 3’000 N for a minimum of 500 cycles with a frequency of 1 Hz (total of 700 cycles for r2 at the minimum). For each run, the stiffness (load-displacement) at the beginning of the tests as well as the development of the stiffness under cyclic loading was recorded. Note that the comparison of the stiffnesses refers to the structural stiffness of the test setups as a whole and not the material stiffness of the pins.
An additional Fe-analysis (finite element analysis) was made to evaluate the load level at which plastic deformation of the pin can be expected.

3.2.4 Test setup using the simplified test model

Before the start of the experiments, five markers (M1 to M5) were fixed on the bone, the pin and a connecting rod to allow recording by a camera (ECO655 MVGE, Monochrome 2448x2050 Pixel, mounted with a f = 40mm lens, SVS Vistek, Seefeld, Germany, analysis with Matrox™ Image Design Assistant, St. Regis Blvd. Dorval, Quebec, Canada). M1 and M2 were attached to the middle of the free length (= 2 cm) of the pin on the lateral and medial side, respectively. M3 and M4 were placed on the dorsal aspect of the bone close to where the pin emerged from the bone laterally and medially, respectively. M5 was used as a reference point in case of movement of the camera and was placed on the middle of the connecting rod of the lateral and medial plates (Fig. 8). The camera took 30 consecutive pictures in 11.6 s every 5 min and registered the movement of the five markers in the X- and Y-direction.

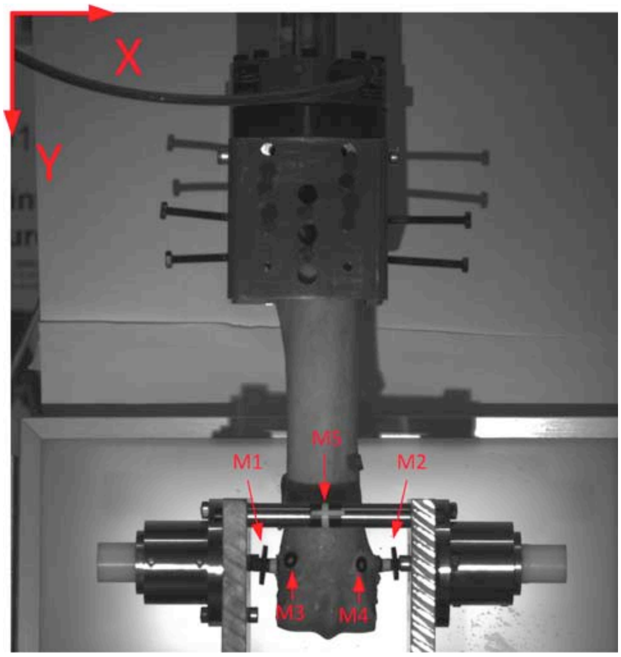

Fig. 8: Positioning of the five markers M1 to M5. The movement of the markers in the X- and Y-direction was by a camera.

The bone with the inserted pin and the attached markers was then mounted on the experimental apparatus. The lateral and medial ends of the pin were inserted into a polyacetal-

copolymer sleeve (POM-C sleeve; E-Modul, ca. 3'000 MPa) with an outer diameter of 2.5 cm and a length of 5 cm. A central hole was drilled through the POM-C sleeve for pin insertion. The diameter of the central hole in the POM-C sleeve was equivalent to the diameter of the inserted pin-end for the first 1 cm (contact area of the pin) and then – towards the ends of the pin – the inner diameter of the central hole was 1.5 cm for the following 4 cm. The POM-C sleeves were always placed 2 cm from the lateral and medial bone surface and were secured by an M4 setscrew on the proximal side of the sleeve. The POM-C sleeves containing the pin-ends were then inserted into an inner stainless steel sleeve (outer diameter = 4 cm, inner diameter = 2.5 cm) and secured with a locking screw. The whole construct containing the pin, the POM-C sleeve and the stainless steel sleeve was then integrated into two vertical side plates containing circular holes for the sleeve constructs (hole diameter = 4 cm) and an outer stainless steel sleeve. The stainless steel sleeves containing the POM-C sleeves were adjusted, so that the distance of the location where the pin emerged from the bone to the beginning of the POM-C sleeve was always 2 cm. The vertical side plates had a height of 30 cm, a width of 15 cm and a thickness of 1 cm. These two vertical plates were attached distally to a ground plate of 10 x 15 cm and kept apart proximally by two stainless steel rods with a length of 10 cm and a diameter of 2 cm (Fig. 7a). To prevent the pins from slipping too far to the lateral or medial side during the cyclic loading, a round profile (diameter = 2.5 cm) was plugged into the stainless steel sleeves on each side, touching the pin ends. The round profiles were fixed by M6 locking screws. Because the SPPPs were longer than the POM-C sleeves, these pins were prevented from slipping by a mechanical limit adapter.
A fixation profile (8 x 10 cm outside dimension) that was attached to the load cell of the testing machine (20 kN hydraulic cylinder with Instron IST control unit 8800, Norwood, Massachusetts, USA) was then moved down until the bone was slightly loaded. The bones were fastened proximally with up to eight M6-screws (depending on bone-size) on each side of the fixation profile (Fig. 9a - b).

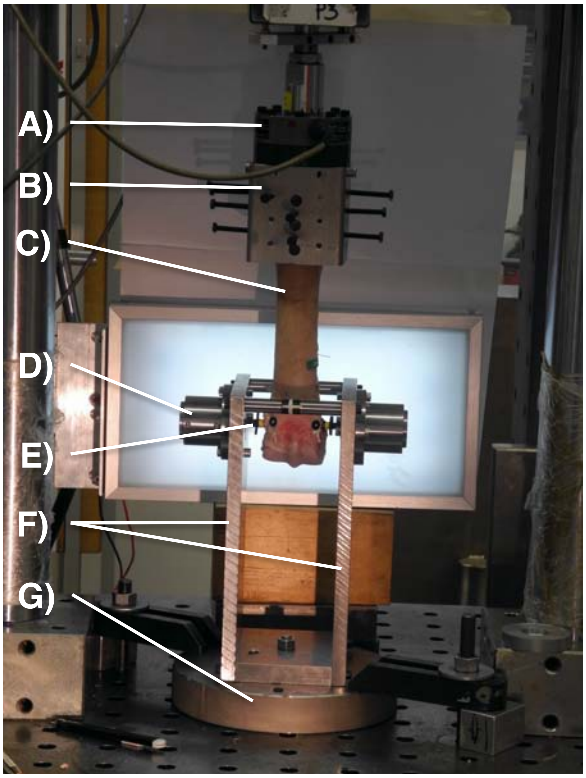

Fig. 9a): Overview of the test setup. A) Load cell, B) fixation profile, C) bone, D) outer stainless steel sleeve, E) pin, F) vertical side plates, G) ground plate.

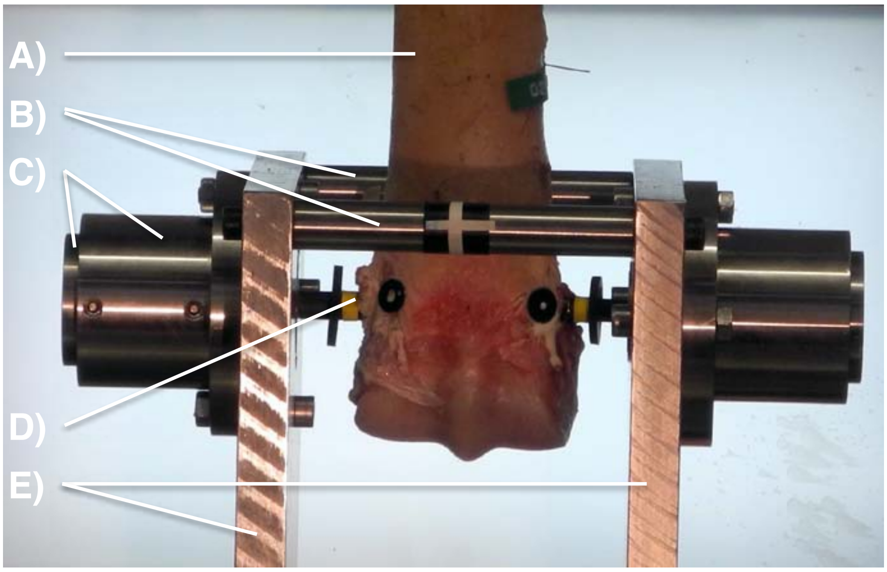

Fig. 9b): Close-up view of the test setup. A) Bone, B) stainless steel rods, C) inner and outer stainless steel sleeves, D) pin, E) vertical side plates.

3.2.5 Biomechanical testing

The bone-pin construct was preloaded with 100 N. The specimens were always loaded in axial compression that led to 4-point pin bending. The first load level 2'000 N was applied with 50 N/s (mean value = 1'050 N with Fo = 100 N, Fu1 = 2'000 N). 10'000 cycles with

load controlled sinusoidal oscillation of 2 Hz were applied on the same load level. The load was faded out during 3 s to the preload of 100 N. For the next load level, the load was raised by 500 N (Fu2 = Fu1 500 N) and the specimen was loaded between Fo = 100 N and Fu2 = 2’500 N for 10’000 cycles. For each following load level, the force was increased by 500 N and lasted for 10’000 cycles until pin failure.
Every Ninc = 20 cycles, the amplitude and the mean value of the load-displacement of the recorded sinus-curve were measured.
The machine was programmed to stop when there was no more resistance from the bone-pin construct (compression force = less than 20 N) or if the displacement was over -20 mm of the initial position of the cylinder.
The statistical software package, IBM SPSS Statistics, was used to test for normal distribution of the data using the Kolmogorov-Smirnov test and to compare the differences of the numbers of endured cycles before pin failure between the pin types, using a paired t-test with p set at <0.05.
Further, the number of cycles sustained by each pin type before a stiffness reduction by 35%, 40% and 50% was achieved, was calculated using the stiffness (N/mm) at the starting point as a reference. Then, a paired t-test was performed to compare the differences of sustained cycle numbers at the stiffness reduction by 35%, 40% and 50% with the p value set at <0.05.
To rule out that the different bone diameters within the groups influenced the outcome, the correlation between the three groups and the bone diameters was evaluated using the comparison of the 95% C.I.. The bone diameters were measured in the metaphysis laterally and medially at the points where pins emerged from the bones. Additionally, we investigated if there is a correlation between the bone diameters and the endured cycle numbers of the bones equipped with ITROP using the Pearson Correlation with the p value set at <0.05.

3.2.6 Radiographic evaluation after biomechanical testing

After biomechanical testing was completed, the bones were examined radiographically once more and also the broken pins that fell out of the bones, were reviewed to evaluate the location of pin breakage and to see if the cyclic loading resulted in any discernible bone damage. For this purpose, a dorsopalmar radiographic projection was obtained and for each specimen, it was noted if the pin was broken on the lateral and/or the medial aspect of the pin and if the pin breakage occurred on the bone surface or within the bone. For the ITROPs, it was registered, if pin failure occurred in the thinner or the thicker TRO-part of the pin and if the pin diameter at the location of pin failure was larger than 7 mm. Furthermore, the bone was examined for fractures and wearing out of the BPI.
To investigate if there was a pin type that showed significantly more cortical wear-out, the odds ratio for the cortical wear-out of each pin type was calculated using the comparison of the 95% C.I..

4 Results

4.1 Case study

The relevant cases included four Warmbloods with an age range between 11 and 16 years. The treated horses were two geldings and two mares and their weights ranged between 480 kg and 620 kg. Three of the fractures were comminuted fractures of P1 and one fracture was a comminuted fracture of P2. The right frontleg was affected twice, the right and left hindleg were affected once each. Horse Nr. 3 had an additional sagittal fracture of the navicular bone on the right hindleg (Tab. 1).

Table 1: Signalement and fracture type.

Horse Nr.	Breed	Sex	Age (Years)	Weight (kg)	Fracture-Type and Location
1	Warmblood	Gelding	15	540	Comminuted closed dislocated biarticular fracture of P1 on the right frontleg with intact strut of bone between MCP and PIP joint
2	Warmblood	Gelding	16	570	Comminuted closed dislocated and collapsed biarticular fracture of P1 on the right frontleg without intact strut of bone between MCP and PIP joint
3	Warmblood	Female	11	480	Comminuted biarticular closed mildly displaced fracture of P2 on the right hindleg (+ right hind sagittal navicular bone fracture)
4	Warmblood	Female	11	620	Comminuted biarticular closed fracture of P1 on left hindleg with intact strut of bone

All four cases were treated with additional internal fixation of the fractures. For all TPCs, two centrally threaded pins were placed initially. In horse Nr. 3, the proximal pin was an ITROP and the distal pin was an IPPP. All other horses had two centrally threaded PPP inserted initially (1 x two 6.2 mm SPPPs, 2 x two IPPPs). The transfixation pins were inserted horizontally into the metaphysis and distal diaphysis of the MCIII and were divergent in the dorsal plane (Tab. 2).

Table 2: Initial therapy.

Horse Nr.	Internal Fixation	Tranfixation Pin Cast			
		Pin Number	**Pin Type**	**Pin Localisation**	**Pin Divergence**
1	7 x 4.5 mm cortex screws in P1	2	6.2 mm SPPP	Distal pin ca. 4 cm proximal to fetlock Proximal pin ca. 2.5 cm proximal to distal pin = pins in metaphysis & distal diaphysis	Pins divergent in dorsal plane
2	4-hole and 5-hole 4.5 mm narrow LCP dorsally +	2	IPPP	Distal pin ca. 5 cm proximal to fetlock	Pins divergent in dorsal plane, not

	3 x 4.5 mm and 1x 3.5 mm cortex screws placed in lag fashion			Proximal pin ca. 3 cm proximal to distal pin = pins in metaphysis & distal diaphysis	placed exactly horizontally
3	1 x 3-hole narrow 4.5/5.0 LCP and 1 x 4-hole 4.5/5.0 mm narrow LCP dorsally + 2 x 4.5 mm cortex screws placed in lag fashion	2	1 x IPPP 1 x ITROP	Distal pin: IPPP ca. 4 cm proximal to fetlock Proximal pin: ITROP ca. 3 cm proximal to distal pin (8.0 mm side lateral) = pins in metaphysis & distal diaphysis	Divergent in dorsal plane
4	8 x 4.5 mm cortex screws placed in lag fashion	2	IPPP	Distal pin ca. 4.5 cm proximal to fetlock Proximal pin ca. 2 cm proximal to distal pin = pins in metaphysis & distal diaphysis	Pins divergent in dorsal plane, not placed horizontally but parallel to each other

All cases showed between one to four pin breakages and the pin breakages occurred between 2 to 28 d after pin insertion. Four times the pin breakage occurred at the proximal pin and five times at the distal pin (once the proximal and distal pins were broken at the same time). Twice the pins were broken at the lateral cortex only and five times the breakages occurred at the medial cortex only. Twice the pins were broken at the lateral and medial cortex (Tab. 3).

Table 3: Pin-related problems.

Horse Nr.	Number of pin-related problem	Proximal vs. distal pin	Type of pin-related problem	Time to occurrence of pin-related problems from previous pin insertion	Location of pin-related problems	Re-surgery
1	1.	Distal pin	Distal bending	2 d	Lateral and medial cortex	Both pins exchanged after 10 d (initial holes)
	2.	Proximal and distal pin	2 x Mild distal bending	1 d	Medial cortex	Both pins replaced after 7 d (new holes ca. 5 and 8 cm proximal to former proximal hole, pins parallel)
	3.	Distal pin	Pin breakage	28 d	Lateral bone surface (BS)	Both pins removed 46 d after 1st surgery
2	1.	Distal pin	Pin breakage	2 d	Medial BS	Distal pin replaced by IPPP after 2 d in a new hole ca. 2.5 cm distal to previous distal hole

	2.	1. Proximal pin 2. Distal pin	1. Pin breakage 2. Mild distal bending	1. Proximal pin: 8 d 2. Distal pin: 6 d	1. Medial BS 2. Medial BS	Proximal pin replaced by IPPP after 6 d in new hole 4 cm proximal to previous proximal hole
	3.	Distal pin	Pin breakage	9 d after replacement of distal pin	Medial cortex	Distal pin removed after 10 d 2 x new 7.6 mm smooth Steinmann pin in initial two holes
	4.	Proximal pin	Pin breakage	17 d after replacement of proximal pin	Medial cortex	All pins removed 25 d after 1st surgery
3	1.	1. Proximal pin 2. Distal pin	1. Pin breakage 2. Pin loosening	11 d	1. Medial cortex	Both pins replaced by ITROP after 14 d (new holes ca. 2.5 and 5.5 cm proximal to former proximal hole, 8.0 mm TRO side lateral)
	2.	Proximal and distal pin	2 x Pin breakage	14 d	Medial and lateral cortex	Both pins replaced by 7.6 mm smooth Steinmann after 15 d (former holes)
	3.	Proximal and distal pin	2 x Pin loosening and pin tract infection & sequester formation	13 d	Medial and lateral cortex	Pins removed 42 d after 1st surgery
4	1.	Distal pin	Pin breakage, pin loosening and mild osteomyelitis	27 d	Lateral cortex	Both pins removed 27 d after 1st surgery

The pins were removed between 25 and 46 d after the initial surgery. Three out of the four horses had to be euthanized due to severe complications. These complications included implant infections of the internal fixation, an intra-articular placed screw, dislocation of the fracture, laminitis and postoperative myopathy. Horse Nr. 4 survived and was discharged from the hospital 66 d after the first surgery with a mild lameness at walk. Approximately one year later, a telephone follow-up revealed that the horse was sound in all gaits and was back to work (Tab. 4).

Table 4: Outcome.

Horse Nr.	Time until Final Pin Removal (after 1st Surgery)	Other Complications	Time until Discharge	Survival
1	46 d	Postoperative myopathy after 1st surgery, Weight-bearing always insufficient Post mortem: severe damage in fetlock joint due to proximal screw located intraarticularly	No discharge	Euthanasia 57 d after 1st surgery
2	25 d	Infection/dehiscence of suture, plates exposed, implant infection P1 Laminitis & pain Beginning formation of sequester around middle and distal pin	No discharge	Euthanasia 29 d after 1st surgery
3	42 d	Laminitis left hindleg, Dislocation of the fracture, Severe implant infection P2 Always very painful	No discharge	Euthanasia 63 d after 1st surgery
4	27 d	-	66 d after 1st surgery (mild lameness at walk)	Horse sound in all gaits and back to work ca. 1 year postop

4.2 Biomechanical testing

4.2.1 Pin insertion and experimental set-up

The preparation of the bones and the insertion of the pins were uneventful. All pins could be inserted without any problems and all bone-pin constructs prepared could be used for biomechanical testing.
The attachment of the bone-pin constructs to the mechanical testing machine and the biomechanical tests proceeded uneventful as well. The only problem observed was pin slipping of the SSP in the first two pairs of bones during cyclic testing. This was solved by adding a round profile that was plugged into the stainless steel sleeves on each side to prevent excessive lateral displacement of the pins for the following experiments. The results of these first two pairs of MCIII were not included in the results of this study.

4.2.2 Results of the pilot study

The comparison of the stiffnesses of the cast model compared to the simplified test model showed that after the first 50 cycles in r1 with a load of Fu = 1’000 N, the stiffnesses were comparable. The simplified test model showed an increased stiffness of 6.7% at that point. With increasing cycle numbers, the stiffness of the cast model decreased by 18.9% after 200 cycles of r1 (Fig. 10a) and 32.7% after 600 cycles of r2, respectively, compared to the starting point. Conversely, the stiffness of the simplified test model showed an increase of 5.8% after 600 cycles of r2 (Fig. 10b).

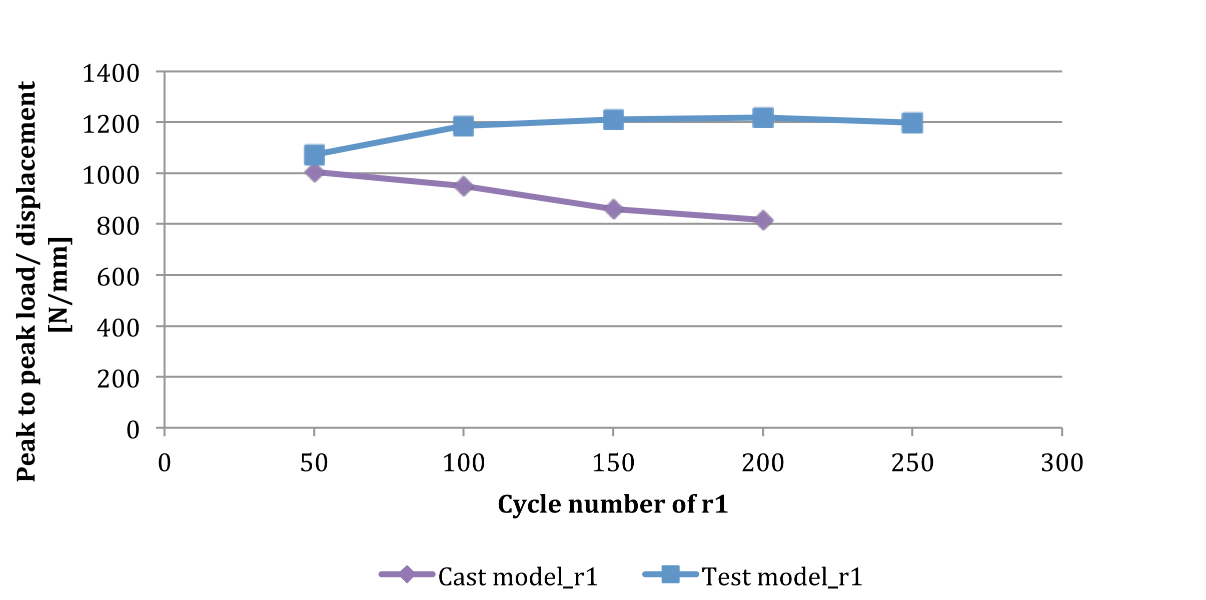

Fig. 10a: Estimated stiffness of the cast model (violet) compared to the stiffness of the simplified test model (blue) in run 1 (r1) at the end of each loading cycle.

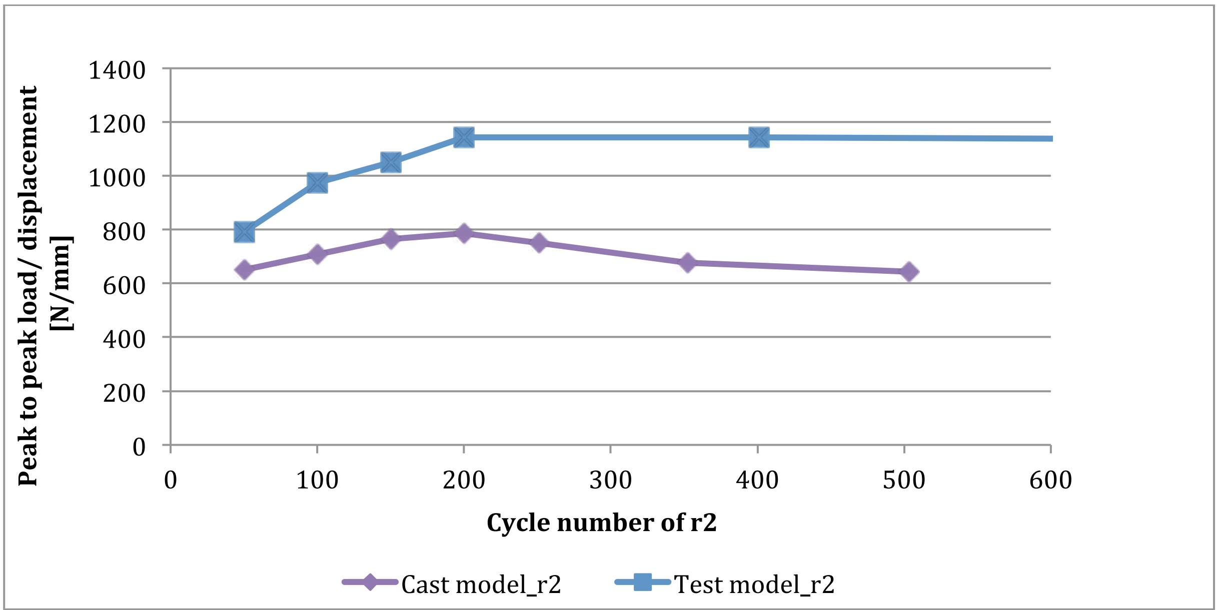

Fig. 10b: Estimated stiffness of the cast model (violet) compared to the stiffness of the simplified test model (blue) in run 2 (r2) at the end of each loading cycle.

The Fe-analysis showed that with a distance of 2 cm from the bone surface to the POM-C sleeve, the plastic deformation is estimated to start at a load around 3800 N (Fig. 11a). Furthermore, the Fe-analysis determined that the location of maximal bending stress sustained by the pins is located at the point at which the pin exits the cortex (Fig. 11b).

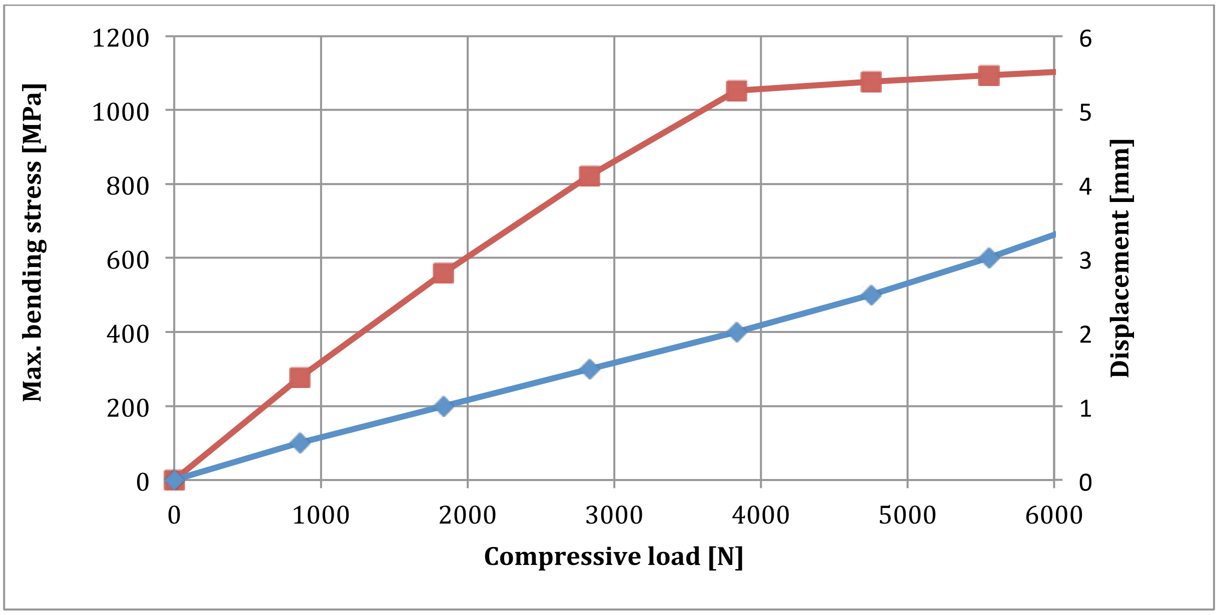

Fig. 11a: Fe-analysis of the maximal bending stress (red) at the compressive testing loads and the displacement (blue) at the compressive testing loads. The plastic deformation is estimated to start at the compressive load around 3800 N.

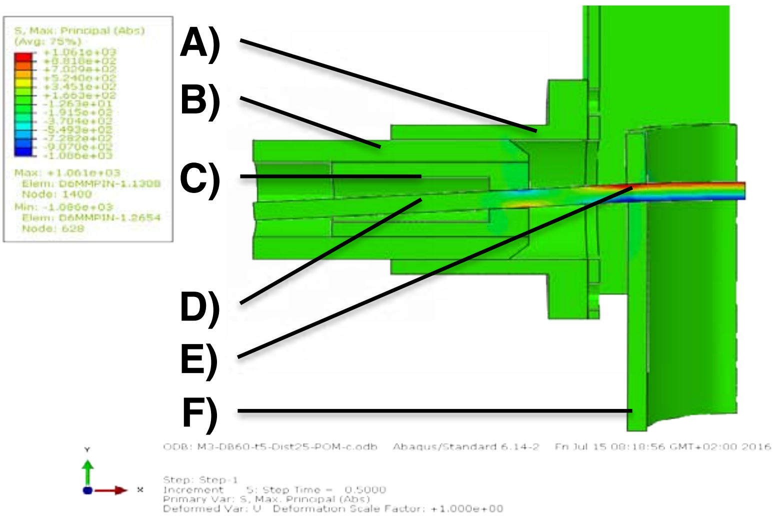

Fig. 11b: Simulation of bending- and tensile stress in Fe-analysis. A) Outer stainless steel sleeve, B) inner stainless steel sleeve, C) POM-C sleeve, D) pin, E) location of the highest bending stress where the pin emerges from the bone cortex (red), F) bone cortex.

4.2.3 Biomechanical testing

The SSP endured a mean 48’685 cycles (SD = 7’869/ 16%) and failed at load levels between 4’000 N and 5’000 N. The SPPP endured a mean of 29’276 cycles (SD = 7390/ 25%) and failed at load levels between 2’500 N and 4’000 N. The IPPP endured a mean of 41’179 cycles (SD = 6’648/ 6%) and failed at load levels between 3’500 N and 4’500 N. The ITROP endured a mean of 31’061 cycles (n = 22: SD = 6’910/ 22%), 25’889 (SD = 2661/ 10%) in the SSP group (1st), 27’689 (SD = 4’008/ 14%) in the SPPP group (2nd), 38’313

(SD = 5'108/ 13%) in the IPPP group (3rd), and failed at load levels between 3'000 N and 4'000 N (Fig. 12a - c).
The Kolmogorov Smirnov test showed that all the data obtained for the endured cycle number before pin failure were normally distributed. The number of cycles before pin failure was significantly higher for the SSP compared to the ITROP ($p = 0.003$). No significant differences in number of cycles before failure were found between ITROP and SPPP ($p = 0.626$) and between ITROP and IPPP ($p = 0.244$).

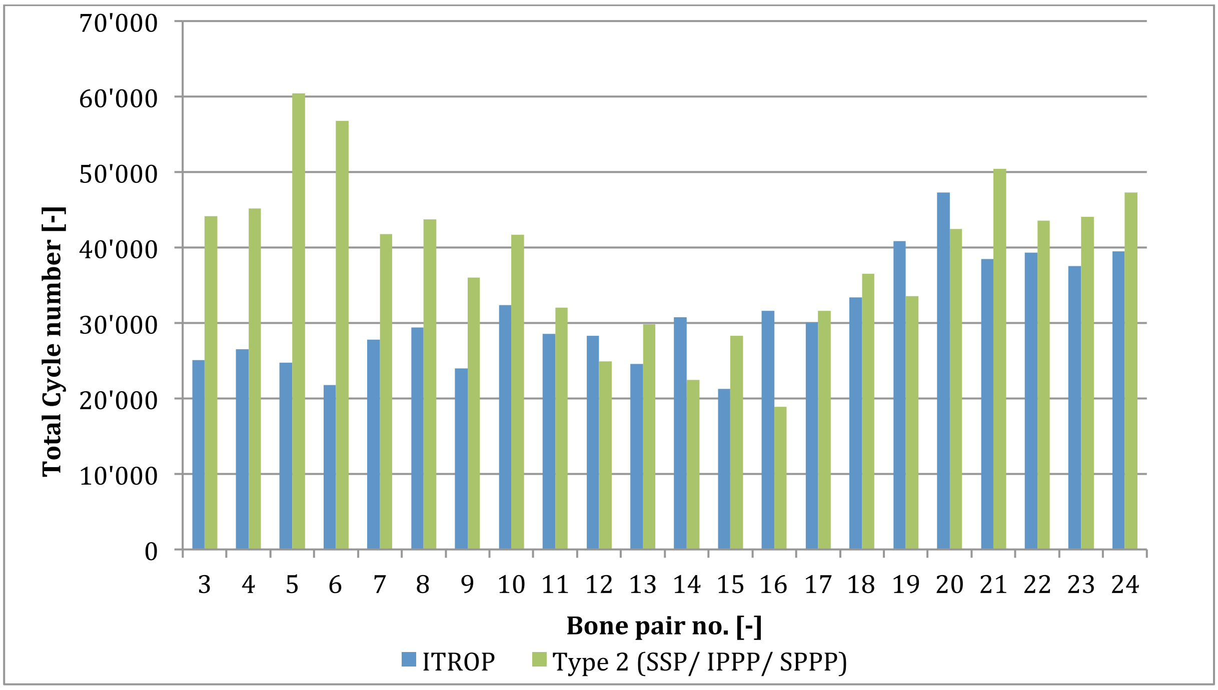

Fig. 12a: Overview of cycle numbers endured before failure of all bone pairs counted in the results.

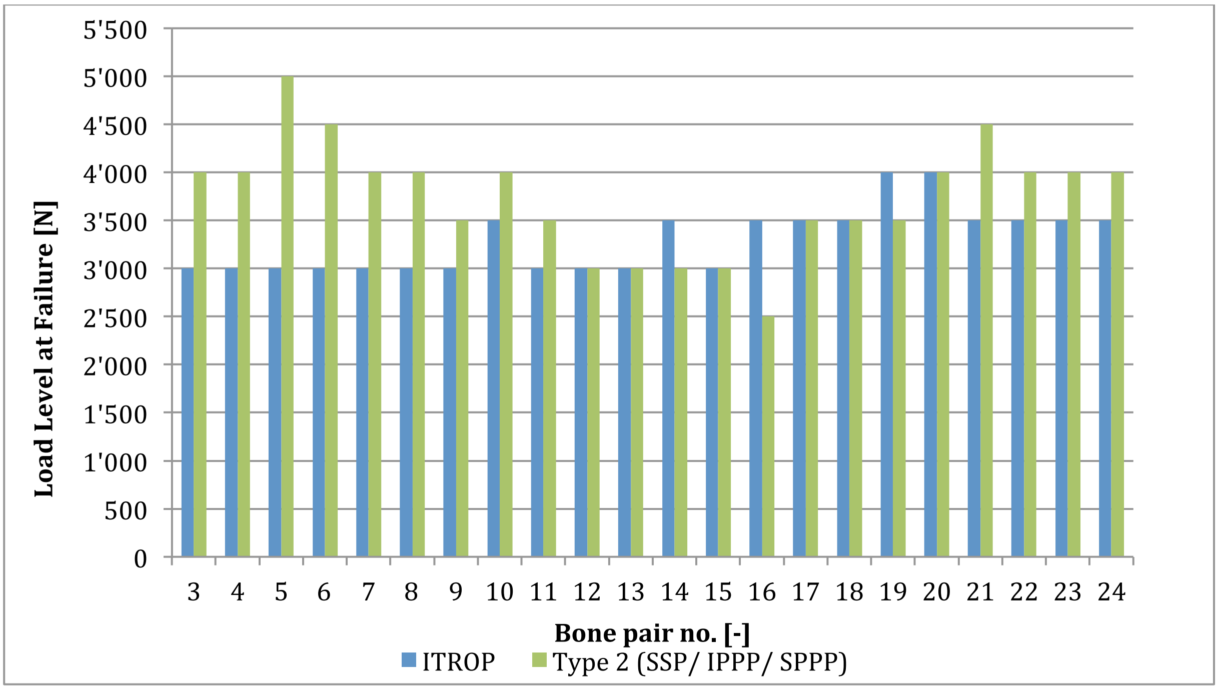

Fig. 12b: Overview of endured load levels at pin failure of all bone pairs counted in the results.

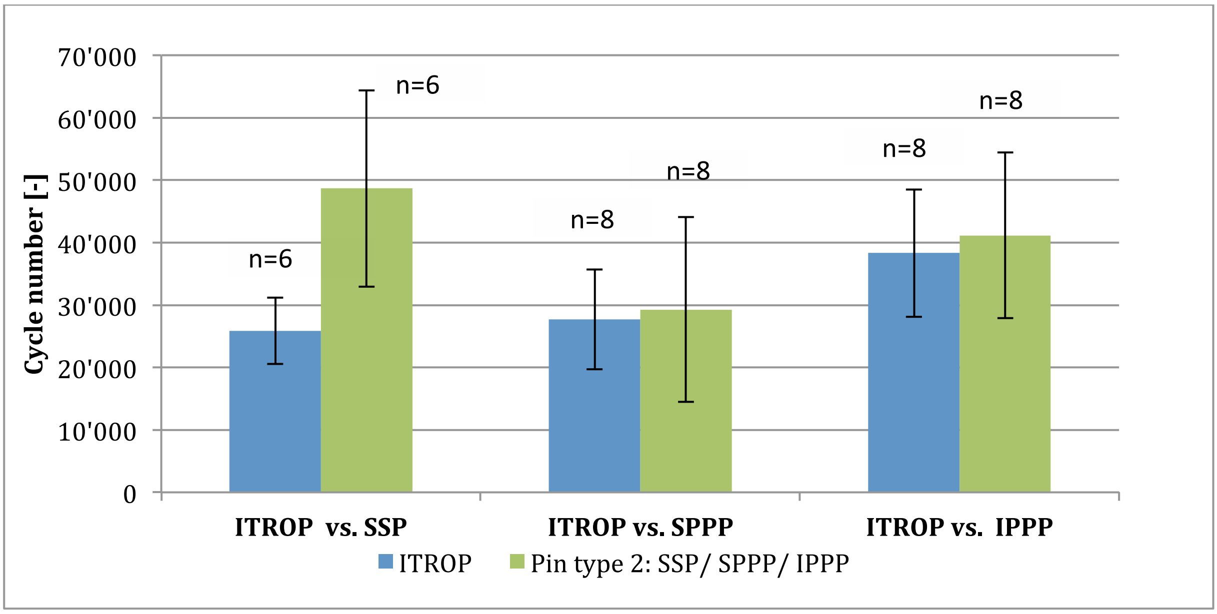

Fig. 12c: Means of endured total cycle numbers of the different pin types. Error bars ± 2 x SD.

The comparison of number of cycles sustained by each type of pin before a reduction in stiffness by 35%, 40% and 50% was achieved showed the same results: these numbers of cycles were significantly higher for SSP compared to ITROP ($p < 0.01$) but there were no significant differences between ITROP and SPPP and between ITROP and IPPP (Fig. 13a-c).

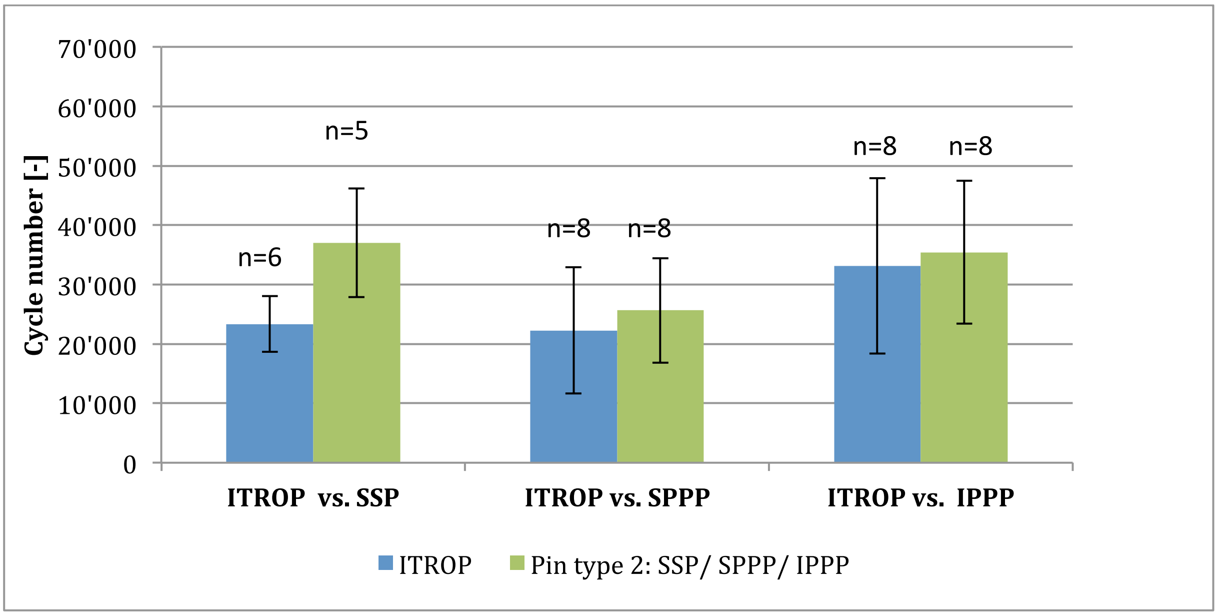

Fig. 13a: Means of cycle numbers sustained before a 35% reduction in stiffness occurred. Error bars ± 2 x SD.

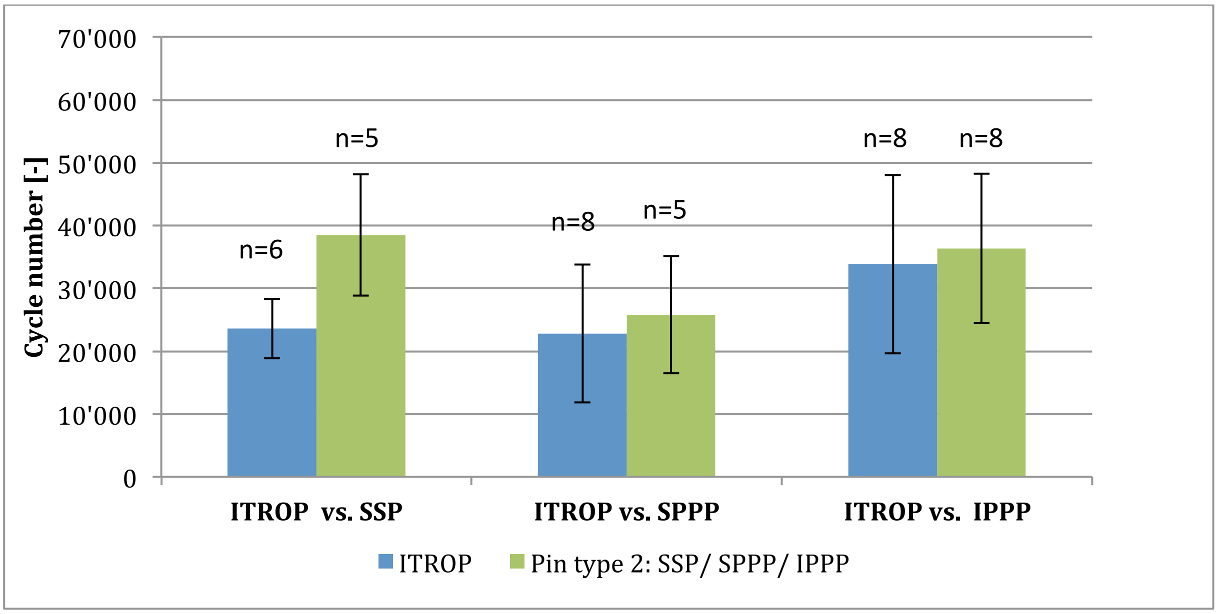

Fig. 13b: Means of cycle numbers sustained before a 40% reduction in stiffness occurred. Error bars ± 2 x SD.

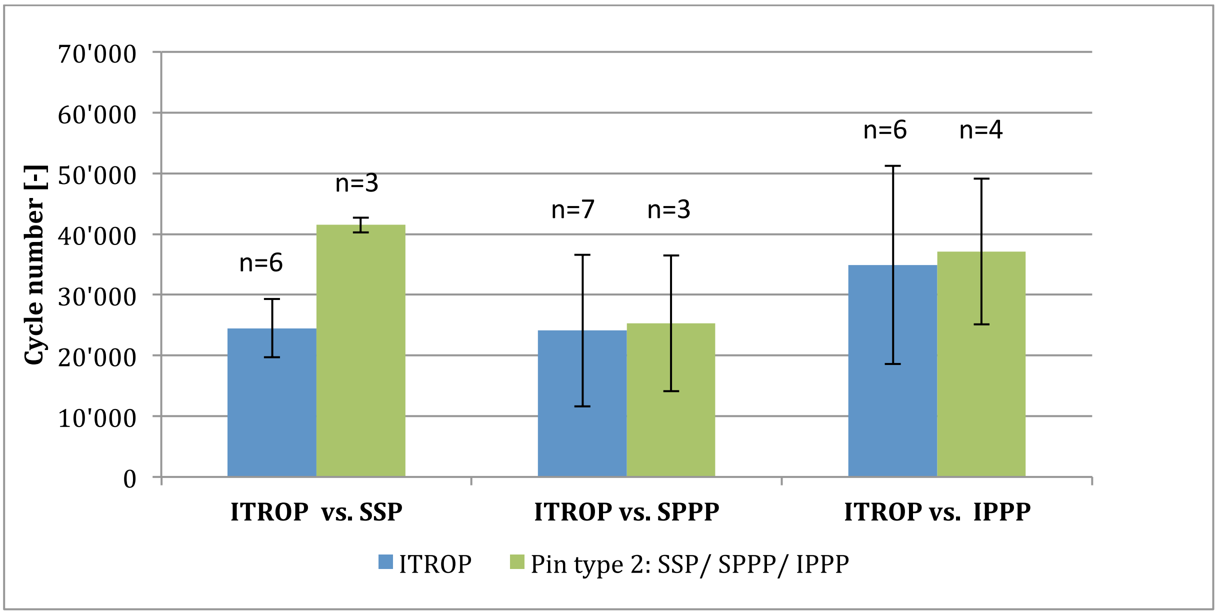

Fig. 13c: Means of cycle numbers sustained before a 50% reduction in stiffness occurred. Error bars ± 2 x SD.

The mean of the bone diameters of the bones with SSP was 57 mm, the mean of the bone diameters of the bones with SPPP was 52.2 mm and the mean of the bone diameters of the bones with IPPP was 52.7 mm. The 95% C.I. for the bones with SSP was 51.7 to 62.3, the 95% C.I. for the bones with SPPP was 48.8 to 55.5 and the 95% C.I. for the bones with IPPP was 49 to 56.3. As all the 95% C. I. were overlapping, there was no significant difference in the bone diameters between the different groups.
The mean of the bone diameters of the bones with ITROP was 53.6 mm. There was also no significant correlation of the bone diameters and the endured cycle number in the bones equipped with ITROP in all three groups ($p = 0.5$).

4.2.4 Failure mode and results of post-testing assessment of the bone-pin constructs

Pin failure (complete or incomplete breakage) on both the medial and lateral aspect was observed in 39 out of 44 pins. Four out of 44 pins (2x SSP, 2x ITROP) showed only lateral pin failure (complete breakage). One pin (SPPP) out of 44 was broken completely only at the lateral aspect but was only deformed without evidence of complete or incomplete breakage at the medial aspect.
Wearing out of the cortices around the pin was noted in 5 out of 6 SSP, 7 out of 8 SPPP, 5 out of 8 IPPP and 7 out of 22 ITROP specimens. The odds ratio for the appearance of wearing out of the cortices was 2.619 (95% C.I. 1.29 – 5.32) when SSPs were compared to ITROPs, 2.75 (95% C.I. 1.41 – 5.35) when SPPPs were compared to ITROPs and 1.96 (95% C.I. 0.87 – 4.43) when IPPPs were compared to ITROP. Therefore, cortical wear-out was significantly more likely when SSPs or SPPPs were used compared to ITROPs. For more details, see Table 5 in the annex.
The ITROPs had bilateral pin failures in 18 pins and 4 unilateral failures at the medial aspect of the pin (which was the thicker, i.e. 8.0 mm diameter, part of this pin designed according to the thread-run out principle). There was no significant difference in the frequency of medial versus lateral pin failure in cases of unicortical pin failures ($p=0.11$).
Fracturing of the bone was observed once in a bone equipped with a SSP that sustained an incomplete metacarpal fracture of the lateral cortex.

5 Discussion

The retrospective analysis of the four clinical cases not only reflects the high complication rate that is associated with treatment of comminuted phalangeal fractures in horses using TPC but also shows that pin breakage plays an important role in this regard. Each of these four horses sustained between one and four pin breakages that occurred between two and 28 days postoperatively. Furthermore, our retrospective study shows that pin breakage can occur with any of the pins that are used most commonly for this indication at the moment, i.e. SPPP, IPPP and ITROP.

Biomechanical testing under cyclic loading conditions compared the ITROP versus three different pins (SSP, SPPP, IPPP). Surprisingly, the only significant difference was the significantly higher number of cycles until failure for the SSP compared to the ITROP. Correspondingly, the SPP failed at higher load levels than the ITROP and a reduction in stiffness by 35%, 40% and 50% occurred at significantly higher cycle numbers for the SSP compared to the ITROP. The other pins (i.e. SPPP, IPPP) did not show a significant better performance than the ITROP. These results are remarkable, even more with regard to the fact that the SSP has the smallest diameter of all pins tested with 6.1 mm. Also in the SSP-group, the stiffness reduction by 35%, 40% and 50%, respectively, occurred at significantly higher cycle numbers compared to the ITROP.

5.1 Case study

The small number of cases and differences with regard to patient characteristics, type of fracture, technique of surgical fixation and postoperative management precludes any statements about the prevalence of pin failures or about the performance of different types of pins. However, this case study illustrates the difficulties and complications experienced with TPC in the horse and indicates that pin breakage occurs regularly and can affect different types of pins that are routinely used.

Three out of four cases described in this study were finally euthanized. In contrast, other case studies showed a short term survival rate of 67% (Kraus et al., 2004), 70% (Joyce et al., 2006), 82% (Rossignol et al., 2014) and 83% (Lescun et al., 2007) of comminuted phalangeal fractures treated with TPC. Most of the surviving horses were used for breeding or leisure activities and showed different degrees of residual lameness (Joyce et al., 2006; Kraus et al., 2004; Rossignol et al., 2014).

The different pins used in our patients were the ones most commonly used by most equine hospitals. As suggested in the literature, all pins were inserted in the metaphysis and distal diaphysis of the MCIII and were diverging in the dorsal plane (Auer, 2012).

Rossignol et al. (2014) always used two 6.35 mm IPPPs. Additional internal fixation was applied if possible (8 out of 11 horses) and consisted of screws placed in lag fashion or arthrodesis performed with two DCPs. The main differences to our study are the coplanar configuration and more distal location of pins (first pin in the epiphysis of MCIII/MTIII, second pin 3 to 4 cm more proximal) and especially the applied hybrid cast described by Rossignol et al. For the hybrid cast, the first layer consisted of plaster of Paris (POP) and the second layer was made of fibreglass. Both layers were put in a figure-of-eight pattern around the pin ends. Additionally, two fibreglass splints were integrated into the cast. Then the pin ends were covered with PMMA (Rossignol et al., 2014).

The study published by Joyce et al. (2006) is retrospective in nature and, therefore, the cases were treated differently. They always used two 6.3 mm pins, except for one case in which three pins were used. Concerning the type of pin, they used five times a SSP and 15 times an IPPP. The pins were inserted between the metaphysis and the proximal diaphysis and were set divergently 9 times and 11 times in a coplanar fashion. In 11 out of 20 cases, additional internal fixation was performed using the placement of cortical screws only or screws in combination with plate fixation (Joyce et al., 2006).

In another study that included different types of phalangeal fractures treated with different fixation methods, those cases that were treated with TPC usually had two threaded pins with a core diameter of 8.6 mm implanted. In some cases, one 8.6 mm threaded pin and two 5.6 mm half pins were used. The first pin was set 1 cm proximal to the physeal scar and the second pin was inserted similarly in the middle diaphysis. The horses treated with TPC had no additional internal fixation initially. Only one horse with a fracture of the MCIII after pin removal was treated with bone plates and bone grafting. Another horse was treated with an arthrodesis of the metatarsophalangeal joint several weeks after initial TPC placement (Kraus et al., 2004).

In our study, all cases showed pin breakage and additional other pin-related complications, such as distal bending, pin loosening and pin tract infection with sequester formation. It is interesting that in the other studies, no pin breakage was observed (Joyce et al., 2006; Kraus et al., 2004; Rossignol et al., 2014), except in one study, where different MC/MT3 and phalangeal fractures where treated and three broken pins and two bent pins were reported (Lescun et al., 2007). Since the thickness of the padding layer directly influences the stability of the TPC construct by determining the lever arm of the bending forces acting on the pins, this could be an important variable contributing to pin breakage. The evaluation of the postoperative radiographs of our cases revealed that the distance between the inner surface of the cast and the outer surface of the bone was always approximately 2 cm. Since the skin, subcutaneous tissue and periosteum in this region are only a few millimeters thin, the thickness of the padding layer is mainly responsible for this distance, and thus the lever arm acting on the pins. There is no detailed information about the thickness of the padding layers in other studies. Methods to reduce the amount of padding material applied during application of a TPC should be considered.

In the study with the hybrid cast of Rossignol et al. (2014), no pin-related complications occurred at all if the pins could be removed after four to six weeks. In one case, the TPC had to remain in place for 12 weeks and then pin loosening and osteomyelitis was observed (Rossignol et al., 2014).

However, in contrast to our study, the other studies reported cases of fractures through a pin hole or of the MCIII in general (Joyce et al., 2006; Kraus et al., 2004; Rossignol et al., 2014). The reasons for these MCIII fractures are thought to be the big pin diameters compared to the bone diameters and the very proximal pin locations (Joyce et al., 2006; Kraus et al., 2004; Rossignol et al., 2014).

In our case study, the TPC was left in place for 25 to 46 days after the first surgery with different numbers of pin exchange. Other studies left the TPC in place for four to eight weeks (Kraus et al., 2004; Rossignol et al., 2014). Joyce et al. (2006) were able to show that horses with TPC left in place for over 40 days showed a significantly better outcome than horses in which the TPC was only left for < 40 days (Joyce et al., 2006).

5.2 Biomechanical testing

5.2.1 Simplified test model

For the biomechanical testing, we chose a simplified test model consisting of the cadaveric bone with one inserted pin and a POM-C sleeve fixation for the pin instead of the TPC model. Such a simplified test model has the advantage that the sources of error like varying thickness of the padding and cast material can be reduced. Also, we decided to use only one pin per bone to ensure the direct comparability of the different pin types without the additional influencing factors of two pins with shared load distribution. With the cast model that was tested beforehand it was shown that in the beginning of the cyclic loading, the used simplified test model with POM-C sleeves, had a similar stiffness to the cast model. The simplified test model showed an increased stiffness of only 6.7% after the first 50 load cycles of r1 with a load of Fu = 1’000 N. But with increasing cycle numbers, the stiffness of the cast model decreased remarkably compared to the start of the cyclic loading, with 18.9% stiffness reduction after 200 cycles of r1 and 32.7% stiffness reduction after 600 cycles of r2. Conversely, the stiffness of the simplified test model even slightly increased with the growing cycle numbers (increment of 5.8% after 600 cycles of r2). We assume that this increment of stiffness can be ascribed to the plastic deformation of the pin and a settlement of the whole test setup. This difference of the stiffness of the two setups is an indication that the pins were tested more critically with the simplified test model than with the cast model. We think that the stiffness of the cast model is reduced more quickly with increasing cycle numbers, because the cast material wears out at the pin-cast interface and the cast shows a higher extent of deformation compared to the POM-C sleeves. But still, the simplified test model provides a comparable alternative with a similar stiffness at the start of the cyclic loading. Clearly, the test setup with POM-C sleeves is correlating better with the cast model compared to test setups with rigid attachment of the pins with screws.

5.2.2 Mode and clinical relevance of biomechanical testing

Cyclic loading by a staircase load increase was the testing method used in this study. Such a testing method has the advantage that it is less sensitive to uncontrollable influencing factors compared to the cyclic loading on one load level. The goal of this method was to induce pin failures on clinically relevant load levels and to allow a comparison of bones equipped with different pin types with an appropriate number of tests. With the given uncertainty prior to the study, a staircase load increase method was, therefore, found to be the appropriate method. Also, the bones showed no significant differences in their diameters and, therefore, allowed a direct comparison of the results.
In vivo studies showed that forces between 2’753.5 N when standing and 7517.5 N when walking occur in the metacarpus of adult horses between 450 and 550 kg (Rybicki et al., 1977). Healthy horses confined to box stalls in a new environment observed over a 24h-period make a mean of 190 (±184) steps per hour, when walking and weight shifting is counted (McDuffee et al., 2000). This results in a mean of 4’560 steps in 24h and 31’920 steps in a week. These values of forces and step numbers correlate well with the failure loads of 2’500 N to 5’000 N and endured cycle numbers of between 29’276 and 48’685 in our biomechanical testing, when the fact that the horses in our case studies were in pain and were,

therefore, expected to spare the affected leg and make less steps in one week. The pin cycle numbers of the biomechanical testing would then correspond to an estimated time to pin breakage of one to two weeks. Additionally, the simplified test model with POM-C sleeves was stiffer with increasing cycle numbers compared to the cast model and, therefore, tested the pins more critically.
Other studies with *in vitro* cyclic loading of transfixation pins used loads between 2’225 N and 3’000 N. They did not test until pin failure but examined, for example, the difference of the resistance to axial extraction before and after cyclic loading. Furthermore, they did not use a staircase load increase but always the same load levels (Bubeck et al., 2010; McClure et al., 2000; Morisset et al., 2000).

5.2.3 Influence of pin design on results of biomechanical testing

For this study, we compared threaded with nonthreaded pins that show essential differences in the design and the material properties. The threaded pins contain more stress-concentrating points like the junction of the threaded to the nonthreaded part as well as surface imperfections (Martens et al., unpublished data). In the ITROP, the acute junction of the threaded to the nonthreaded part is alleviated due to the increasing shaft diameter and decreasing thread depth.
The outcome of our biomechanical testing showed that SSP have the significantly highest breaking strength under cyclic loading conditions. On the other hand, previous studies showed that smooth pins have a decreased holding power and, therefore, tend to loosen faster under cyclic loading (Anderson et al., 1993; Aron et al., 1986; Clary and Roe, 1995; Egger et al., 1986; Palmer et al., 1992). These findings correlate with the fact that, in our biomechanical tests, the SSP showed a higher amount of lateral displacement under axial loading (Fig. 14).

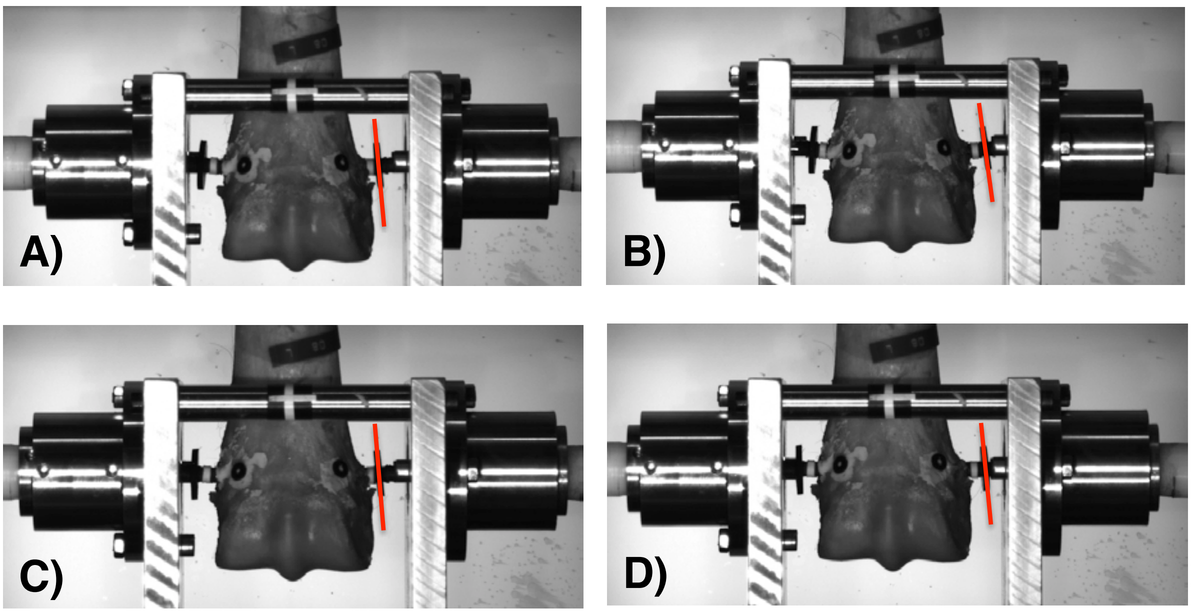

Fig. 14: Illustration of the lateral displacement of the same SSP with increasing cycle numbers. The red line highlights the lateral displacement and was drawn through the M2 marker. A) to B), Displacement of the pin to the right. B) to C), Displacement of the pin back to the left. C) to D), Recurrent displacement of the pin to the right.

We suggest that the remarkable higher amount of the lateral displacement in the SSP had a positive effect on the breaking strengths of the pins. As the pin gets loose and begins to wander, it is not always stressed at the same two points where the pin emerges from the bone. This leads to a less critical testing of the pin and a higher breaking strength. In this study, the lateral displacement was controlled by the plugged-in round profiles on each side of the pins. But it was still observed that the SSP showed more lateral movement compared to the threaded pins.

As mentioned in the introduction, premature pin loosening is the most common complication of ESF (Aron and Toombs, 1984; Aron et al., 1986; Clary and Roe, 1995; Egger et al., 1986; Joyce et al., 2006; Morisset et al., 2000; Palmer et al., 1992) and is associated with reduced stability of the fracture site and pain (Auer, 2012; Clary and Roe, 1995; Joyce et al., 2006; Lescun et al., 2012; Morisset et al., 2000; Palmer et al., 1992). Pin loosening is thought to promote pin tract infections that can lead to ring sequestrum formation, osteomyelitis and secondary fractures through a pin hole due to enlarged pin holes (Aron and Toombs, 1984; Aron et al., 1986; Auer, 2012; Clary and Roe, 1995; Green, 1981; Lescun et al., 2012; Nunamaker and Nash, 2008; Palmer et al., 1992).

The SSP and SPPP showed significantly more cortical wear-out compared to ITROP. The cortical wear-out is associated with pin loosening and bone weakening as the bone defect is increased and, therefore, may promote catastrophic failure through the pinhole.

The wearing out also leads to a prolonged effective lever arm. As the bending moment is the product of the lever arm times the applied force (Palmer et al., 1992), the prolonged lever arm results in an enhanced bending moment of the pin and, therefore, these pins were tested more critically. For the IPPP, the results of the wearing out were not significantly different compared to the ITROP. For the SSP, the main reason for wearing out is thought to be the absence of threads and the concomitant increased extent of lateral displacement and pin loosening as discussed above. The explanation for the increased wearing out of the bones equipped with SPPP is unclear as the pin design is very similar to the IPPP.

One additional factor with a large impact on the outcome is the diameter of the different pin types. For this study, the most common pins that are currently available on the market and are frequently used in the clinics were tested. Clearly, there is a wide range of additional pin types and diameters available on the market, that were not considered in our study.

For this study the variation of the pin diameters ranged from 6.1 to 6.3 mm, and the ITROP even had a diameter of 8 mm on the TRO side of the pin. Since the stiffness of the pin increases by the fourth power of the radius increment (Palmer et al., 1992), it is evident that these variations have a high impact on the breaking strengths of the pin.

We could not show any significant difference of the medial vs. lateral location of pin breakage for the ITROP. This is remarkable as the medial side has an increased diameter of 8 mm in addition to the TRO design of the thread, compared to the 6.3 mm diameter and normal positive thread on the lateral side. This change of diameter is also associated with a change of stiffness within the pin. Therefore, some areas of the pin are tested more critically than others and are more stressed. With the results of this study, the importance and benefits of the TRO thread discovered in the studies for small animals of Griffin et al. (2011) cannot be confirmed for the use in large animals.

5.2.4 Influencing factors and variations of the test setup

The test setup was chosen so that it corresponded as closely as possible to the actual clinical situation. Obviously, there are many factors that influenced the outcome of our studies, including the possible failure mechanisms occurring under cyclic loading and the inherent variations of the test setup.
First, the variations of the bone diameters at the level of pin entry and exit were expected to be important. Importantly, there was neither a significant difference of the bone diameters between the groups nor a correlation of bone diameter and endured cycle number. It is assumed that the length of the lever arm and not the bone diameter is the main critical factor. As the pins were inserted manually and cadaveric bones were used, it could not be guaranteed that all the pins were placed exactly horizontally and exactly equally in every bone, even though an aiming device and x-ray control were used. When a bone is loaded with a pin not placed absolutely rectangular to the bone, shear forces always lead to lateral displacement of the pin.
Another mechanism that contributed to some variations of the results is the variation of the sample preparations (test setup). These variations include small differences in the distance of the POM-C sleeve to the bone surface, varying slackness between the POM-C sleeve and the pin as well as the different extent of micromotion of the pin depending on the shear forces. Finally, potential differences of the material properties within the pin types could also contribute to variations of the results.

5.2.5 Limitations of the biomechanical study

Limitations of this biomechanical study include the unintended variations of the test setup as mentioned above. The simplified test setup has the advantage that uncontrollable influencing factors are reduced and the pilot study showed that, biomechanically, it is a valid model. However, the differences to the clinical situation are an inherent limitation – e.g. it is unclear if the lateral displacement of the pins with its consequences on stress distribution that occurred in this *in vitro* situation also occurs in a real transfixation cast construct. The use of cadaveric limbs is closer to the clinical situation than the use of artificial bones, but the effects of all biological processes such as bone response, osteointegration and local infection, are largely neglected. Furthermore, the test setup does not allow the evaluation of the different characteristics of a specific pin such as material properties, diameter and design on its overall mechanical performance. Finally, the material properties of the different pin types used were not examined any further.

5.3 Conclusions

The first hypothesis that pin breakage can occur clinically with any of the pins currently available for TPC could be confirmed, as all pins broke under clinically relevant load levels and cycle numbers. The second hypothesis that the new ITROP is biomechanically superior to the SPPP, the IPPP and the traditional SSP under cyclic loading conditions relevant for equine TPC patients, was not confirmed, as the performance of the ITROP was not superior to the other pin designs under the given testing-mode.

The SSP showed a significantly higher number of endured loading cycles compared to all other pin types, even though they showed more lateral displacement and cortical wear-out. This implements that the focus of the selection of the pin type for TPC should not only be on the fixation of the pin in the bone and thus resistance to axial extraction and pin loosening but also consider the resistance to bending stress under cyclic loading.
The limitations of this biomechanical study using a simplified test model do not allow a direct advice for the clinical use of the different pin types. Clearly, further *in vivo* studies are necessary.

7 References

Anderson, M.A., Mann, F.A., Wagnermann, C., Hahn, A.W., Jiang, B.L., Tomlinson, J.L., 1993. A Comparison of Nonthreaded, Enhanced Threaded, and Ellis Fixation Pins Used in Type-I External Skeletal Fixators in Dogs. Vet Surg 22, 482-489.

Aron, D.N., Toombs, J.P., 1984. Updated Principles of External Skeletal Fixation. Comp Cont Educ Pract 6, 845-858.

Aron, D.N., Toombs, J.P., Hollingsworth, S.C., 1986. Primary Treatment of Severe Fractures by External Skeletal Fixation: Threaded Pins Compared with Smooth Pins. J Am Anim Hosp Assoc 22, 659-670.

Auer, J.A. 2012. Principles of Fracture Treatment, In: Auer, J.A., Stick, J.A. (Eds.) Equine Surgery (Fourth Edition). W.B. Saunders, Saint Louis, Missouri, 1047-1081.

Brianza, S., Brighenti, V., Boure, L., Sprenger, V., Pearce, S., Schwieger, K., 2010. In Vitro Mechanical Evaluation of a Novel Pin-Sleeve System for External Fixation of Distal Limb Fractures in Horses: A Proof of Concept Study. Vet Surg 39, 601-608.

Bubeck, K.A., Garcia-Lopez, J., Maranda, L.S., 2009. In Vitro Comparison of Cortical Bone Temperature Generation between Traditional Sequential Drilling and a Newly Designed Step Drill in the Equine Third Metacarpal Bone. Vet Comp Orthop Traumatol 22, 442-447.

Bubeck, K.A., Garcia-Lopez, J.M., Jenei, T.M., Maranda, L.S., 2010. In Vitro Comparison of Two Centrally Threaded, Positive-Profile Transfixation Pin Designs for Use in Third Metacarpal Bones in Horses. Am J Vet Res 71, 976-981.

Clary, E.M., Roe, S.C., 1995. Enhancing External Skeletal Fixation Pin Performance - Consideration of the Pin-Bone Interface. Vet Comp Orthop Traumatol 8, 6-13.

Edgerton, B.C., An, K.-N., Morrey, B.F., 1990. Torsional Strength Reduction Due to Cortical Defects in Bone. J Orthop Res 8, 851-855.

Egger, E.L., Histand, M.B., Blass, C.E., Powers, B.E., 1986. Effect of Fixation Pin Insertion on the Bone-Pin Interface. Vet Surg 15, 246-252.

Elce, Y.A., Southwood, L.L., Nutt, J.N., Nunamaker, D.M., 2006. Ex Vivo Comparison of a Novel Tapered-Sleeve and Traditional Full-Limb Transfixation Pin Cast for Distal Radial Fracture Stabilization in the Horse. Vet Comp Orthop Traumatol 19, 93-97.

Eriksson, A.R., Albrektsson, T., 1983. Temperature Threshold Levels for Heat-Induced Bone Tissue Injury: A Vital-Microscopic Study in the Rabbit. J Prosthet Dent 50, 101-107.

Green, S.A. 1981. Pin Tract Infection, In: Complications of External Skeletal Fixation: Causes, Prevention and Treatment. Charles C. Thomas, Springfield, 12-30.

Griffin, H., Toombs, J.P., Bronson, D.G., Ross, J.D., Browne, R.H., 2011. Mechanical Evaluation of a Tapered Thread-Run-out Half-Pin Designed for External Skeletal Fixation in Small Animals. Vet Comp Orthop Traumatol 24, 257-261.

Hanson, P.D., Markel, M.D., 1994. Radiographic Geometric Variation of Equine Long Bones. Am J Vet Res 55, 1220-1227.

Hopper, S.A., Schneider, R.K., Johnson, C.H., Ratzlaff, M.H., White, K.K., 2000. In Vitro Comparison of Transfixation and Standard Full-Limb Casts for Prevention of Displacement of a Mid-Diaphyseal Third Metacarpal Osteotomy Site in Horses. Am J Vet Res 61, 1633-1635.

Hopper, S.A., Schneider, R.K., Ratzlaff, M.H., White, K.K., Johnson, C.H., 1998a. Effect of Different Full-Limb Casts on in Vitro Bone Strain in the Distal Portion of the Equine Forelimb. Am J Vet Res 59, 197-200.

Hopper, S.A., Schneider, R.K., Ratzlaff, M.H., White, K.K., Johnson, C.H., 1998b. Effect of Pin Hole Size and Number on in Vitro Bone Strength in the Equine Radius Loaded in Torsion. Am J Vet Res 59, 201-204.

Huiskes, R., Chao, E.Y.S., Crippen, T.E., 1985. Parametric Analyses of Pin-Bone Stresses in External Fracture Fixation Devices. J Orthop Res 3, 341-349.

Joyce, J., Baxter, G.M., Sarrafian, T.L., Stashak, T.S., Trotter, G., Frisbie, D., 2006. Use of Transfixation Pin Casts to Treat Adult Horses with Comminuted Phalangeal Fractures: 20 Cases (1993-2003). J Am Vet Med Assoc 229, 725-730.

Kraus, B.M., Richardson, D.W., Nunamaker, D.M., Ross, M.W., 2004. Management of Comminuted Fractures of the Proximal Phalanx in Horses: 64 Cases (1983-2001). J Am Vet Med Assoc 224, 254-263.

Lescun, T.B., Baird, D.K., Oliver, L.J., Adams, S.B., Hawkins, J.F., Moore, G.E., 2012. Comparison of Hydroxyapatite-Coated and Uncoated Pins for Transfixation Casting in Horses. Am J Vet Res 73, 724-734.

Lescun, T.B., McClure, S.R., Ward, M.P., Downs, C., Wilson, D.A., Adams, S.B., Hawkins, J.F., Reinertson, E.L., 2007. Evaluation of Transfixation Casting for Treatment of Third Metacarpal, Third Metatarsal, and Phalangeal Fractures in Horses: 37 Cases (1994-2004). J Am Vet Med Assoc 230, 1340-1349.

Lopez, M.J., Markel, M.D. 2012. Bone Biology and Fracture Healing, In: Auer, J.A., Stick, J.A. (Eds.) Equine Surgery (Fourth Edition). W.B. Saunders, Saint Louis, Missouri, 1025-1040.

Martens, A., Valkova, V., Pinto da Silva, E., Petrov, R., Saunders, J., Declercq, J., Pille, F., unpublished data. Pin Breaking as a Serious Complication in Three Cases of Comminuted P1 Fractures Treated with Transfixation-Pin Casting.

McClure, S.R., Hillberry, B.M., Fisher, K.E., 2000. In Vitro Comparison of Metaphyseal and Diaphyseal Placement of Centrally Threaded, Positive-Profile Transfixation Pins in the Equine Third Metacarpal Bone. Am J Vet Res 61, 1304-1308.

McClure, S.R., Honnas, C.M., Watkins, J.P., 1995. Managing Equine Fractures with External Skeletal Fixation. Comp Cont Educ Pract 17, 1054-1063.

McClure, S.R., Watkins, J.P., Ashman, R.B., 1994a. In-Vitro Comparison of the Effect of Parallel and Divergent Transfixation Pins on Breaking Strength of Equine 3rd Metacarpal Bones. Am J Vet Res 55, 1327-1330.

McClure, S.R., Watkins, J.P., Bronson, D.G., Ashman, R.B., 1994b. In-Vitro Comparison of the Standard Short Limb Cast and 3 Configurations of Short Limb Transfixation Casts in Equine Forelimbs. Am J Vet Res 55, 1331-1334.

McClure, S.R., Watkins, J.P., Hogan, H.A., 1996. In Vitro Evaluation of Four Methods of Attaching Transfixation Pins into a Fiberglass Cast for Use in Horses. Am J Vet Res 57, 1098-1101.

McDuffee, L.A., Stover, S.M., Coleman, K., 2000. Limb Loading Activity of Adult Horses Confined to Box Stalls in an Equine Hospital Barn. Am J Vet Res 61, 234-237.

Morisset, S., McClure, S.R., Hillberry, B.M., Fisher, K.E., 2000. In Vitro Comparison of the Use of Two Large-Animal, Centrally Threaded, Positive-Profile Transfixation Pin Designs in the Equine Third Metacarpal Bone. Am J Vet Res 61, 1298-1303.

Muir, P., Johnson, K.A., Markel, M.D., 1995. Area Moment of Inertia for Comparison of Implant Cross-Sectional Geometry and Bending Stiffness. Vet Comp Orthop Traumatol, 146-152.

Nash, R.A., Nunamaker, D.M., Boston, R., 2001. Evaluation of a Tapered-Sleeve Transcortical Pin to Reduce Stress at the Bone-Pin Interface in Metacarpal Bones Obtained from Horses. Am J Vet Res 62, 955-960.

Nemeth, F., Back, W., 1991. The Use of the Walking Cast to Repair Fractures in Horses and Ponies. Equine Vet J 23, 32-36.

Nunamaker, D.M., Nash, R.A., 2008. A Tapered-Sleeve Transcortical Pin External Skeletal Fixation Device for Use in Horses: Development, Application, and Experience. Vet Surg 37, 725-732.

Nunamaker, D.M., Richardson, D.W., 1992. External Skeletal Fixation in the Horse. Proceedings of the Thirty-Seventh Annual Convention of the American Association of Equine Practitioners, 549-555.

Nunamaker, D.M., Richardson, D.W., Butterweck, D.M., Provost, M.T., Sigafoos, R.D., 1986. A New External Skeletal Fixation Device That Allows Immediate Full Weightbearing Application in the Horse. Vet Surg 15, 345-355.

Nutt, J.N., Southwood, L.L., Elce, Y.A., Nunamaker, D.M., 2010. In Vitro Comparison of a Novel External Fixator and Traditional Full-Limb Transfixation Pin Cast in Horses. Vet Surg 39, 594-600.

Palmer, R.H., Hulse, D.A., Hyman, W.A., Palmer, D.R., 1992. Principles of Bone Healing and Biomechanics of External Skeletal Fixation. Vet Med Small Anim Clin 22, 45-68.

Rossignol, F., Vitte, A., Boening, J., 2014. Use of a Modified Transfixation Pin Cast for Treatment of Comminuted Phalangeal Fractures in Horses. Vet Surg 43, 66-72.

Rybicki, E.F., Mills, E.J., Turner, A.S., Simonen, F.A., 1977. In Vivo and Analytical Studies of Forces and Moments in Equine Long Bones. J Biomechanics 10, 701-705.

Schneider, R.K., Ratzlaff, M.C., White, K.K., Hopper, S.A., 1998. Effect of Three Types of Half-Limb Casts on in Vitro Bone Strain Recorded from the Third Metacarpal Bone and Proximal Phalanx in Equine Cadaver Limbs. Am J Vet Res 59, 1188-1193.

Seltzer, K.L., Stover, S.M., Taylor, K.T., Willits, N.H., 1996. The Effect of Hole Diameter on the Torsional Mechanical Properties of the Equine Third Metacarpal Bone. Vet Surg 25, 371-375.

Williams, J.M., Elce, Y.A., Litsky, A.S., 2014. Comparison of 2 Equine Transfixation Pin Casts and the Effects of Pin Removal. Vet Surg 43, 430-436.

Zacharias, J.R., Lescun, T.B., Moore, G.E., Van Sickle, D.C., 2007. Comparison of Insertion Characteristics of Two Types of Hydroxyapatite-Coated and Uncoated Positive Profile Transfixation Pins in the Third Metacarpal Bone of Horses. Am J Vet Res 68, 1160-1166.

6 Acknowledgment

First of all, I would like to thank Prof. Dr. Anton Fürst for giving me the opportunity to write my doctor's thesis on this interesting subject and for providing data, material and support.

My sincere gratitude goes to Dr. Jan Kümmerle, my supervisor, for his constant support in the development, execution and completion of this thesis. Thanks for all the ideas, discussions, advice, invested time, helping hands in the practical work and most of all for the good collaboration.

Acknowledgements go to Bernhard Weisse and his group for 'Biomedical Engineering and Structural Mechanics' of the Empa Dübendorf, for making the biomechanical tests possible. A thousand thanks go to Sebastian Valet for his tireless effort in the development of the test setup, his countless invested hours in the performance of the tests and for his patient explanations and support in the analysis of the data.

Thanks to Paul Müller and Kathrin Süss for providing me with the bones and the storage location. I also want to thank the whole team of the Equine Hospital of the University of Zurich for all the practical help during the preparation of the specimens. A special thank goes to med. vet. Marco Bryner for the good collaboration and the helping hands.

I thank Prof. Dr. Ann Martens of the Department of Surgery and Anaesthesiology of Domestic Animals, Faculty of Veterinary Medicine, Ghent University, Belgium, for providing ideas and advice as well as testing material for this thesis.

Finally, I want to thank my family and friends for their constant encouragement and support to help making this thesis possible. Sincere thanks go to my father for his special help and advice during the process of the completion of this thesis and for his technical support.

7 Curriculum Vitae

Vorname Name	Sara Keller
Geburtsdatum	10.12.1988
Geburtsort	Zürich
Nationalität	Schweiz
Heimatort	Basel

August/1995 - Juli/2001	**1. - 6. Primarschule** (Schulhaus Langmatt, Zürich, Schweiz)
August/2001 - Juli/2004	**1. - 3. Sekundarschule A** (Schulhaus Looren B, Zürich, Schweiz)
August/2004 - September/2008	**1. - 4. Kurzzeitgymnasium** (Kantonsschule Stadelhofen, Zürich, Schweiz)
03.09.2008	**Matura** (Kantonsschule, Stadelhofen, Zürich, Schweiz)

September/2008 - Dezember/2014	**Studium der Veterinärmedizin** an der Vetsuisse Fakultät Universität Zürich, Zürich, Schweiz
30.12.2014	**Abschlussprüfung** med. vet. Vetsuisse-Fakultät Universität Zürich, Zürich, Schweiz

Oktober/2015 – Januar/2018	**Anfertigung der Dissertation**
	unter Leitung von Prof. Dr. Anton Fürst, Direktor Klinik für Pferdechirurgie und betreut durch Dr. Jan Kümmerle, Departement für Pferde Vetsuisse-Fakultät Universität Zürich
Seit September/2016	**Assistenztierärztin**, Zentrum für Tiermedizin Klettgau, Neunkirch, Schweiz

8 Annex

Table 5: Follow-up of the bones

Pin Nr./ Side	**Pin-Type**	**Pin medial aspect** (x-ray and visual findings)	**Pin lateral aspect** (x-ray and visual findings)	**X-ray medial cortex**	**X-ray lateral cortex**	**Other findings**
3/right	SSP	Complete breakage bone surface (BS)	Incomplete breakage BS	-	Wearing out of pin tract	
3/left	ITROP	Complete breakage BS	Complete breakage BS	-	-	
4/right	SSP	Incomplete breakage inside bone	Complete breakage BS	Worn out	Worn out	Incomplete metacarpal fracture
4/left	ITROP	Complete breakage BS	Complete breakage BS	-	-	
5/right	ITROP	Complete breakage BS	Complete breakage BS	-	-	
5/left	SSP	Complete breakage inside bone	Incomplete breakage inside bone	Worn out	Worn out	
6/right	ITROP	Complete breakage BS	Bending	-	-	
6/left	SSP	Complete breakage inside bone	Complete breakage inside bone	Worn out	Worn out	
7/right	ITROP	Complete breakage BS	-	Worn out	Worn out	
7/left	SSP	Complete breakage inside bone	Bending	-	Worn out	
8/right	ITROP	Complete breakage BS	Incomplete breakage BS	-	-	
8/left	SSP	Complete breakage inside bone	-	-	-	
9/right	SPPP	Complete breakage inside bone	Complete breakage inside bone	Worn out	Worn out	
9/left	ITROP	Complete breakage BS	Complete breakage BS	-	-	
10/right	SPPP	Complete breakage	Incomplete breakage	Worn out	Worn out	Lateral displacement of the pin → data questionable, location of breakage not defined
10/left	ITROP	Complete breakage BS	Complete breakage BS	-	-	

11/right	SPPP	Incomplete breakage and deformation at BS	Complete breakage BS	-	-	
11/left	ITROP	Complete breakage BS	Complete breakage BS	-	-	
12/right	SPPP	Complete breakage cortex	Complete breakage cortex	Worn out	Worn out	
12/left	ITROP	Complete breakage cortex	Complete breakage BS	Worn out	-	
13/right	ITROP	Complete breakage BS	Complete breakage BS	-	-	
13/left	SPPP	Complete breakage BS	Complete breakage BS	Worn out	Worn out	
14/right	ITROP	Complete breakage cortex	Complete breakage BS	Worn out	-	
14/left	SPPP	Bending at cortex	Complete breakage inside bone	Worn out (mild)	Worn out	
15/right	ITROP	Complete breakage BS	Complete breakage cortex	-	Worn out (mild)	
15/left	SPPP	Complete breakage BS	Incomplete breakage and deformation at cortex	-	Worn out (mild)	
16/right	ITROP	Complete breakage BS	Complete breakage BS	-	-	
16/left	SPPP	Complete breakage BS	Incomplete breakage inside bone	-	Worn out (severe)	
17/right	IPPP	Complete breakage BS	Complete breakage BS	-	-	
17/left	ITROP	Complete breakage BS	Complete breakage cortex	-	Worn out (mild)	
18/right	IPPP	Complete breakage cortex	Complete breakage inside bone (inner cortex)	Worn out (mild)	Worn out	
18/left	ITROP	Complete breakage BS	Complete breakage BS	-	-	
19/right	IPPP	Complete breakage BS	Complete breakage BS	-	-	
19/left	ITROP	Complete breakage cortex	Complete breakage BS	Worn out (mild)	-	
20/right	IPPP	Complete breakage BS	Complete breakage cortex	-	Worn out (mild)	

20/left	ITROP	Complete breakage BS	Incomplete breakage BS	-	-	
21/right	ITROP	Complete breakage cortex	Complete breakage cortex	Worn out (mild)	Worn out (mild)	
21/left	IPPP	Complete breakage cortex	Complete breakage cortex	Worn out	Worn out	
22/right	ITROP	Complete breakage cortex	Complete breakage inside bone	Worn out (mild)	Worn out	
22/left	IPPP	Complete breakage cortex	Incomplete breakage and deformation inside bone	Worn out (mild)	Worn out	
23/right	ITROP	Complete breakage BS	Complete breakage BS	-	-	
23/left	IPPP	Complete breakage BS	Complete breakage BS	-	-	
24/right	ITROP	Complete breakage BS	Complete breakage BS	-	-	
24/left	IPPP	Complete breakage BS	Incomplete breakage and deformation inside bone	-	Worn out (mild)	